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# A STUDY OF IGNITION PRESSURE SPIKING IN ATTITUDE CONTROL ENGINES

## VOLUME II

## A COMPARISON OF NITROGEN TETROXIDE/MONOMETHYLHYDRAZINE AND HYDROGEN PEROXIDE/MONOMETHYLHYDRAZINE IGNITION PRESSURE SPIKING CHARACTERISTICS

By

R. N. Gurnitz
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Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May 1967

Contract NAS9-6134

Rocketdyne
A Division of North American Aviation, Inc.
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AND HYDROGEN PEROXIDE/MONOMETHYLHYDRAZINE
IGNITION PRESSURE SPIKING CHARACTERISTICS

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## FOREWORD

This report has been prepared in compliance with National Aeronautics and Space Administration Contract NAS9-6134. The effort on this contract was conducted during the 10-month period from 1 July 1966 through 30 April 1967 by the Rocketdyne Research Division. This volume of the report covers effort expended from 1 March 1967 to 30 April 1967.

## ACKNOWLEDGMENTS

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## ABSTRACT

A study was conducted to compare the noncatalytic altitude ignition characteristics of the $N_2O_4$/MMH and 98 percent $H_2O_2$/MMH propellant combinations. All tests were conducted with a 91-pound-thrust, 150-psia chamber pressure combustor with a 16-element (unlike doublet) splash plate design injector. The simulated altitude was 150,000 feet; nominal temperatures were 100 F.

The two firings with the $H_2O_2$/MMH propellants resulted in injector-damaging pressure spikes in the 3500-psi range. These were considerably in excess of the average ignition spikes of 325 psi noted during the 114 $N_2O_4$/MMH tests.

The effects of valve timing and ignition delay on spiking for the $N_2O_4$/MMH combination were noted and discussed. For this propellant combination, uncorrected c* efficiencies of approximately 94 percent were found.

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## SUMMARY

A brief program was conducted for the purpose of comparing the noncatalytic altitude igntion and performance characteristics of the $N_2O_4$/MMH and the 98 percent $H_2O_2$/MMH propellant combinations. The test facilities and hardware employed were similar to those used in the catalytic phase of the program (Volume I). Only those system modifications dictated by peroxide compatibility requirements were made.

All tests were conducted in a nominally 91-pound-thrust, 150-psia chamber pressure, combustor. The injector was 16 element (unlike doublet) splash-plate design. The simulated preignition altitude was 150,000 feet, and propellant and hardware temperatures were kept at 100 F.

For the 114 successful $N_2O_4$/MMH tests conducted, the average of the ignition pressure spikes was 325 psi. Only two of the tests had spike pressures greater than 1000 psia. The approximate spiking pressures for these tests were 2145 and 3645 psia. For the nominally employed mixture ratio of 2.0 an uncorrected c* efficiency of $94.1^{+1.6}_{-1.3}$ percent was found.

The $N_2O_4$/MMH data were analyzed for the effect of valve timing on spiking magnitude. A maximum in the average spiking level was found at an oxidizer lead of approximately 5 milliseconds (lead in introduction of oxidizer to chamber). For the $N_2O_4$/MMH data, no correlation between spiking magnitudes and the estimated variations in ignition delay was found. The variations were estimated to be a maximum of $\pm 0.9$ millisecond. No absolute measurements of ignition delay were made. The average sums of the manifold fill time and ignition delay were found to be 13.5 and 20.0 milliseconds for fuel and oxidizer, respectively.

Two firings were conducted with the $H_2O_2$/MMH propellant combination. The first resulted in two pressure spikes 13 milliseconds apart, and magnitudes

of 3200 and 2300 psia, respectively. Both the injector and splash plate were damaged. The injector was dished in the upstream direction, and the splash plate was dished in the downstream direction. The second firing, conducted with a new injector and splash plate, was characterized by a single pressure spike of approximately 3400 psia. Both the injector and splash plate were damaged as in the previous test. During both tests the O-ring seal between the injector and splash plate was unseated. The resulting gas leakage and an unstable combustion condition precluded the obtaining of meaningful c* data.

Ignition delays for the $H_2O_2$/MMH system were estimated to be 8 to 10 milliseconds greater than for the $N_2O_4$/MMH system. It was concluded that the $H_2O_2$/MMH altitude ignition characteristics were considerably more severe than the $N_2O_4$/MMH ignition characteristics. It was further concluded that the $H_2O_2$/MMH ignition characteristics are of such severity as to preclude its use in thrustors of the type employed, i.e., ones in which a splash plate injection system is used.

# INTRODUCTION

As discussed in Volume I of this report (Ref. 1), ignition of the hypergolic $N_2O_4$/hydrazine-type-fuel propellant combinations under altitude conditions usually is accompanied with a pressure spike. This spike is typically coincident with initial chamber pressure rise and is characterized by rise times in the submillisecond range. Because such ignition characteristics are undesirable it was decided to investigate the ignition characteristics of another propellant combination, 98 percent $H_2O_2$/MMH. To effect a direct comparison with the $N_2O_4$/MMH propellants, a combination presently in use, a test program was designed to test both combinations under identical conditions.

A limited amount of bipropellant peroxide effort had been accomplished previously (Ref. 2). Employing a flat-face injector of what was at that time (1960) state-of-the-art design, a series of six 90 percent $H_2O_2/N_2H_4$ firings were conducted. These resulted in hard starts and generally rough combustion. For the six firings conducted, three resulted in burned injectors, one in a cracked injector, and one in an oxidizer manifold explosion. Another, in a throatless motor, was characterized by rough burning.

Subsequent $H_2O_2/N_2H_4$ work was carried out with an $N_2O_4$ slug start. These resulted in nondestructive, relatively smooth ignitions. The resulting combustion was characterized, however, by intermittent high-frequency, low-amplitude, chamber pressure oscillations. $H_2O_2$/UDMH and $H_2O_2$/JP-5 combinations were also discussed in Ref. 2. Hypergolic slugs were employed with these, and results similar to the $H_2O_2/N_2H_4$ work were obtained.

For the present work, the test facilities and hardware employed were similar to those used during the catalytic phase of the program (Volume I of this report). Only system modifications dictated by peroxide compatibility requirements were made. A major modification required was with the main valves. Slower response, higher void-volume Marotta valves were substituted for the peroxide incompatible Rocketdyne valves. Because system ignition characteristics are influenced by the valve characteristics and because a direct comparison of the two propellant combinations was desired, it was necessary to conduct another series of $N_2O_4$/MMH firings, in addition to those discussed in Volume I.

As discussed in Volume I, different modes of ignition pressure spiking are possible depending on pulse history. For the present work, it was of interest to study spiking which occurred during operation in which the volumes downstream of the valve poppets would completely empty between pulses. Pulse train operation was investigated first. However, complete manifold emptying did not occur with the typical pulse trains used. Therefore, the method of testing was changed to a single-pulse operation with off-times between pulses of typically 3 to 5 minutes. Further, a hardware and propellant temperature of 100 F was selected to enhance the chance of manifold emptying.

# EXPERIMENTAL APPARATUS AND PROCEDURE

## EXPERIMENTAL HARDWARE

### Thrust Chamber

A reaction control engine configuration, similar to that of the Apollo Command Module RCS engine, was used for the program. A solid-wall, water-cooled thrust chamber was used in place of the ablative Apollo RCS thrust chamber. Key thrust chamber design parameters were:

| | |
|---|---|
| Throat diameter, inches | 0.710 |
| Contraction ratio | 3.2 |
| Contraction half angle, degrees | 20 |
| Characteristic length, inches | 11.3 |
| Nozzle expansion ratio | 15 |

An assembly drawing and photograph of the chamber are presented in Fig. 1 and Fig. 2. The chamber was also used for the work reported in Volume I of this report. The thrust chamber consisted of an integral copper chamber and nozzle section drilled with internal cooling passages and encased in a stainless-steel sheath. A pressure transducer port compatible with a water-cooled Kistler transducer was located in the chamber wall just upstream of the start of nozzle convergence.

Temperature conditioning was accomplished by pumping the conditioning water through the cooling passages. Prerun steady-state chamber temperature measurements were obtained from a thermocouple attached directly to the outside of the copper chamber.

## Splash Plate Injector

A splash-plate injector configuration similar to that of the Apollo Command Module RCS engine, was used for the experimental effort. The stainless-steel injector assembly was in two pieces, an injector and a splash plate. The injectors were obtained by machining the splash plate from Apollo injectors. The face pattern was comprised of 16 unlike impinging doublets equally spaced in a circle with the fuel and oxidizer orifices placed on 0.48 and 0.36 inch radii, respectively. The integral valves were removed from the injector and a mechanical fitting was installed for close-coupling the main valves. A photograph of the injector is shown in Fig. 3.

The stainless-steel splash plates were identical to the Apollo splash plate design with one exception. Instead of being integral with the injector as in the Apollo design, the splash plate was a separate segment positioned in front of the injector.

## Main Valves

The Apollo Command Module RCS engine main valves, utilized for the effort reported in Volume I, could not be used in this effort because of incompatibility with the hydrogen peroxide. Internal components of the Apollo valve were fabricated from 400 series stainless steel, a material not chemically compatible with the peroxide.

The final selection of valves, Marotta Model MV43SA, was based chiefly on availability. The Marotta valve (Fig. 4) is solenoid operated with an appreciably longer coil saturation time than the Apollo valve (33 ms as compared to 8 ms). However, once saturated, the valve opening time is comparable (approximately 2.7 ms for the Marotta valve as compared to approximately 1.3 ms for the Rocketdyne valve). The Marotta valve had a larger internal volume and also could not be connected to the injector with the same degree of close-coupling as the Apollo valve, so that overall manifold filling times were longer (13.5 ms and 20.0 ms for the fuel and oxidizer respectively, as compared to ~9 ms and ~6 ms).

Valve Actuation Measurement. Main valve opening and closing was monitored by measuring a voltage signal from an induction coil wrapped around the Marotta valve solenoid coil. The induction coil picked up the magnetic flux from the operating coil when it was energized, and also detected the armature motion due to its effect on the magnetic field. Figure 5 shows typical traces of the output of the monitoring coils. As the operating coil was energized the voltage across the monitoring coil rose, then began to decay because the energizing current was no longer changing. The movement of the armature changed the magnetic field strength and induced an additional voltage across the monitoring coil that appeared as a peak in Fig. 5. A typical Kistler transducer output is also shown in Fig. 5.

## DATA RECORDING

Data was recorded as shown in Table 1 on either one or a combination of the following recording instruments:

1. Hieland Model 712C, 60 channel oscillograph, 0 to 3 Khz response, CEC type 1-127 AC amplifiers, Dana Model 3840 DC amplifiers, Rocketdyne-designed, solid-state, emitter follower amplifiers for Rocketdyne flowmeters
2. Beckman Offner Type R Dynalog, 0 to 200 hz response, 8 channel

3. Tektronix Type 545 oscilloscope, 0.01 microsecond rise time

4. Ampex Model 5-3459 Tape Recorder, 7 channel, 0 to 10 Khz response

5. MKS Instruments, Type 77 Baratron Pressure Meter (Baratron referenced to a Stokes McLeod Gage, Flosdorf type range 0 to 500 microns)

6. Foxboro Cell Type Dynalog Recorder, Model 9420 TV

7. Foxboro EMF Type Dynalog Recorder Model 9330A

8. Bailey Meter, Model EX00, Circular Chart Type Recorder

### Data Playback Instrumentation

The magnetic tape records of the Kistler pressure transducer, a 1000-hz timing pulse, and the Rocketdyne high response flowmeters which were simultaneously made on the Ampex Model 5-3459 recorder/reproducer at 60 ips were replayed at 7-1/2 ips on an Ampex FR100-7 recorder/reproducer. The output from the FR100-7 was recorded by a 7-inch, CEC, 18-channel oscillograph. The paper speed on the latter was 27 inches per second.

The system playback response was limited by the oscillograph galvanometers which were rated at 5 Khz. Since the data were played back at 1/8 of the original speed, the overall limiting response in the tape recording/reproducing system was the real time 0 to 10 Khz response of the Model 5-3459 recorder.

## EXPERIMENTAL FACILITIES

The experimental firings were conducted at the Flame Laboratory test stand located at the Rocketdyne Santa Susana Field Laboratory. Photographs of the test stand are presented in Fig. 6 and 7.

## Propellant Flow Systems

Schematic diagrams of the $N_2O_4$/MMH and $H_2O_2$/MMH flow systems are shown in Fig. 8 and 9. The $N_2O_4$/MMH flow system was identical to that used in the effort reported in Volume I of this report. Helium was used as the pressurant gas for both 250-cu in. propellant tanks. Gaseous nitrogen purge systems and liquid flush systems were used to clear the propellant lines, main valves, and injector manifolds at the close of the firing day. Isopropyl alcohol and Freon TF were used as the liquid flush for the fuel and oxidizer systems, respectively. A propellant recirculation system was included, except with the $H_2O_2$ system, to recirculate the propellants from the lines upstream of the main valve to the propellant tanks. This eliminated gas pockets in the lines and aided in temperature conditioning of the propellants.

The oxidizer system was modified to accomodate the $H_2O_2$/MMH testing effort (Fig. 9 ). This involved the substitution of passivated propellant tankage, a new fill system, removal of the Rocketdyne flowmeter, and cleaning and passivating the valves and propellant lines.

## Temperature Conditioning System

A schematic of the temperature conditioning system is shown in Fig. 10. The system was that used in the original program effort (Volume I of this report). Because the conditioning temperature was 100 F for these experiments, water was used as the conditioning fluid. Separate conditioning tanks and hardware recirculation systems were used for the thrust chamber, the fuel and oxidizer propellant lines, the fuel tank, and the oxidizer tank. Variac controlled, higher power (4 and 2 kilowatt) heating elements were used in conjunction with a thermostatically controlled 500 watt heating element for temperature control.

### Vacuum Chamber

Test conditions included firing at a simulated altitude of 150,000 feet. Altitude simulation was accomplished by firing the thrust chamber into a 21-cubic-foot vacuum tank which was evacuated by a large capacity vacuum pump (Kinney Model No. KC 46). Vacuum pump oil (tricresylphosphate) compatible with the propellant exhaust products was employed.

## EXPERIMENTAL PROCEDURE

Two series of tests were accomplished: a series of short-duration firings with the $N_2O_4$/MMH propellant combination, and a series with the 98-percent $H_2O_2$/MMH combination. The testing procedures are discussed in three parts: (1) a prerun checkout, (2) testing, and (3) postrun stand shutdown.

### Prerun Checkout

The prerun checkout procedure was to ready the stand for testing. This included hardware assembly, flow system checks, instrumentation checks, and conditioning system activation and adjustment.

The hardware was assembled and attached to the vacuum chamber and the main valves. This included the injector, splash plate, and chamber sections. Following this, a complete flow system check was made, including a systematic check of the valves. The propellant run tank level was checked and propellant was added as required. The conditioning system was actuated, the conditioning baths were filled with water, and adjustments to the system were made to maintain the conditioned temperatures within the desired ranges.

Instrumentation checks were made on all pressure and flowmeter transducers. The Kistler transducers were calibrated with a vacuum tube voltmeter each day, and were calibrated on tape periodically. Other pressure transducers were "zeroed" and an electrical calibrate throw (80 percent of range signal) was obtained. (The pressure transducers were normally calibrated once a month.) The thermocouples were checked for continuity, and the flowmeters were checked for operation when the propellants were recirculated just prior to the countdown. The tape channels, oscillograph channels and galvanometers, and the direct-inking oscillograph channels were checked for correct operation. The oscilloscope used to display the leading valve trace and a Kistler trace was also checked for correct operation.

## Testing Procedure

Immediately prior to each test, the vacuum chamber was evacuated, and final adjustments were made to the propellant and chamber conditioning systems. The main valves actuation circuits were connected and the valve lead-lag control adjusted to give the proper value.

The steps taken immediately prior to a firing were as follows:

1. The propellant prevalves were opened.
2. The propellant tanks were pressurized.
3. The propellant line and injection and chamber temperatures were read from a Leeds and Northrup millivolt potentiometer.
4. The test pit fire extinguishing system and sequencer were armed.
5. The altitude chamber vacuum conditions were read.
6. The oscilloscope camera shutter was opened.

A four step countdown and firing sequence was made as follows:

| | | |
|---|---|---|
| One | - | The tape recorder was turned on. |
| Two | - | (count only) |
| Three | - | (count only) |
| Fire | - | The Eagle sequencer was actuated. |

Also, at the command of "Fire", the oscillographs and circular recording charts were started. Approximately 2 seconds later the main valves were opened. The Eagle sequencer was used to control the test duration to between 10 and 20 milliseconds for the majority of the runs. However, at least one test each day was run for a longer duration (> 300 milliseconds) to obtain performance data and to maintain a check on the system.

The vacuum pump remained on throughout the short-duration firings. When the vacuum tank altitude reached an acceptable level and the oscilloscope camera had been reloaded, the next test was made by starting the four-step countdown. The vacuum pump oil was contaminated after 5 to 10 tests (depending on the propellant lead-lag conditions) and it was necessary to replace the oil if the required vacuum was to be obtained in a reasonable length of time.

Preliminary spiking data were obtained by simultaneously monitoring the leading valve and a Kistler transducer on the oscilloscope. Both traces were recorded by a Polaroid camera. The camera lens was set on a time exposure and both traces were triggered to sweep across the oscilloscope by the electrical signal to the leading fast-acting valve. Spiking data and ignition delay times were obtained from the simultaneous recordings of both valve signatures (induced voltages) and Kistler transducer traces on a high-response tape recorder.

## Posttest Procedure

The vacuum tank was brought to ambient pressure and purged. The hardware was then separated at the injector splash plate interface so the splash plate could be removed and inspected. The $N_2O_4$ and MMH propellant valves were purged and flushed before securing the stand for the day. The $H_2O_2$ system was not purged, and the valves were not flushed when securing the stand. This was to minimize the possibility of introducing contaminents to the system.

## DATA REDUCTION PROCEDURES

The data reduction effort was directed to both the spiking results and injector performance. The injector performance was calculated as c* (full-shifting expansion) efficiency by ratioing a calculated c* to the theoretical value. The experimental c* values were calculated as:

$$c^* = \frac{P_c A_t g}{\dot{w}_t}$$

This data was available for only the few long-duration tests. No corrections for heat loss, friction, or throat discharge coefficient were applied.

The high-response pressure spiking and ignition delay data was obtained from the Kistler transducer output recorded on the FM tape recorder, speed reduced, and reproduced on a galvanometer oscillograph.

PROPELLANT COMPOSITIONS

Chemical analyses were performed on the propellants used for testing. These analyses are presented below:

A. $N_2O_4$ (green NTO) (Density of 1.459 gm/ml at 60 F)

| | |
|---|---|
| $N_2O_4$, percent | 99.2 |
| NO , percent | 0.65 |
| NOCl, percnet | 0.004 |
| $H_2O$, percent | 0.08 |

Conforms to MSC PPD-2A for components analyzed

B. $H_2O_2$ (98 percent $H_2O_2$)

| | |
|---|---|
| $H_2O_2$, percent | 97.4 |

Conforms to Mil P16005D for component analyzed

C. Monomethylhydrazine (MMH) (Density of 0.870 gm/ml at 77 F)

| | |
|---|---|
| $N_2H_3CH_3$, percent | 99.6 |
| $H_2o$, percent | 0.2 |
| $NH_3$, percent | 0.1 |
| Soluble Impurities, percent | 0.1 |
| $CH_3NH_2$ | trace |

Conforms to Mil P-27404 for components analyzed

## RESULTS AND DISCUSSION

The objectives of this phase of the program were to compare the noncatalytic ignition and c* performance characteristics of the $N_2O_4$/MMH and $H_2O_2$/MMH propellant combinations. This comparison was made over a range of relative valve timings and at a common propellant and chamber temperature of 100 F.

### $N_2O_4$/MMH EVALUATION

Data were obtained for 114 $N_2O_4$/MMH firings. Of these, 7 firings were of sufficient duration (300 milliseconds or greater) to obtain steady-state c* data. The rest were characterized by chamber pressure pulse widths of about 5 to 10 milliseconds. A summary of all data obtained is presented in Table 2.

#### Determination of Oxidizer Lead

As discussed in the Apparatus section of this report, the motion of each main valve was monitored by sensing the voltage induced in a secondary coil wrapped around the primary solenoid coil. From such data, the time between oxidizer valve full-open position and fuel valve full-open position was accurately determined. In Table 2 , this was recorded as "mechanical Oxidizer Lead, milliseconds". The values (+ and -) refer to the time period between the oxidizer valve reaching a full-open position and the fuel valve reaching a full-open position.

From the simultaneously recorded valve motion and high-response Kistler pressure transducer data, the time between the fuel valve full-open position and first indication of chamber pressure was ascertained. This is shown in Table 2 as "Time from Fuel Valve Full Open Position to $P_c$, milliseconds".

A plot of the time from fuel valve full-open position to chamber pressure rise vs the mechanical fuel valve lead is shown in Fig. 11. From the point where the two lines intersect, the mechanical fuel valve lead time, which corresponds with simultaneous arrival of propellants at the injector face, was determined to be -6.5 milliseconds. From this value, and the previously discussed Mechanical Oxidizer Lead, the oxidizer lead at the injector face was determined. These are shown in Table 2 as "Calculated Oxidizer Lead, milliseconds".

Effect of Valve Timing

The effect of valve timing on the average of the maximum igntion to steady-state pressure ratios was evaluated by averaging the pressure ratios in the oxidizer lead ranges shown in Table 3. A plot of the average spike ratio vs oxidizer lead at the injector is presented in Fig. 12. As shown in Fig. 12, a maximum occurred in the vicinity of a 5 milliseconds oxidizer lead. This was also evident for other $N_2O_4$/MMH propellant temperature/chamber temperature combinations (Volume I).

Effect of Ignition Delay

The average of the sums of the fuel manifold fill times and ignition delays was 13.5 milliseconds (Fig. 11). The average of the sums of the oxidizer manifold fill times and ignition delays was therefore 13.5 + 6.5, or 20.0 milliseconds. From the existing data, however, it is not possible to separate the ignition delay from the average sums.

If it is assumed that the fill times are resonably constant, variations in the sums would reflect the variations in the ignition delay. For each of the six oxidizer lead intervals shown in Table 3 , the ratio of the maximum to steady-state pressures are plotted vs the sums of the manifold fill times and ignition delays (Fig. 13). No relationship between spiking pressure ratio and variation in ignition delay is suggested. If one existed, it would be expected that increasing spiking ratios would have occurred for increases in ignition delay.

## Distribution of Data

For each of the oxidizer lead ranges given in Table 3 , the distributions of maximum to steady-state pressure ratios were evaluated. For the intervals of +24.4 to +25.3 milliseconds, +9.9 to +16.0 milliseconds, -0.1 to +2.4 milliseconds, and -7.8 to -11.2 milliseconds, the distributions exhibited normal characteristics. These are shown in the approximately linear relationships of the plots in Fig. 14 . The interval of -33.8 to -37.2 milliseconds contained only three data points, too few for such an analysis.

The interval of +3.2 to +5.7 milliseconds did not exhibit normal distribution characteristics (Fig. 15 ). As shown in Fig. 12 , large changes in $P_s/P_c$ occurred for very small changes in oxidizer lead during the +3.2 to +5.7 interval. It is therefore expected that the distribution characteristics for that interval were different from those of the other intervals in which only very moderate changes in spiking ratio occurred.

## Combustion Performance - c* Efficiency

The combustion performance of the $N_2O_4$/MMH propellant combination was determined for gross comparison with the $H_2O_2$/MMH combination. The determination of performance was not a primary goal in the effort, and the experimental apparatus used resulted in several compromises to an accurate determination of performance. However, gross differences between the propellants could have been detected. Unfortunately, the unstable nature of the $H_2O_2$/MMH firing precluded any performance calculations.

The characteristic velocity calculations were accomplished using chamber pressure as measured at the injector face, weight flowrates, and the average of the prerun and postrun throat areas. The chamber pressure value was not corrected to the total pressure at the throat (as per the definition of c*) because of the unknown pressure loss characteristics across the splash plate. Also, no corrections were made for heat loss, friction, throat area discharge coefficient, or area change resulting from transient heating.

Seven firings were of sufficient duration to establish steady flow and pressure conditions. The results of these tests are summarized in Table 4 An average c* efficiency of 94.1 percent of the theoretical shifting value was measured. The measured c* efficiencies range of 92.8 to 95.7 percent was obtained for mixture ratios of from 1.91 to 2.13. The c* efficiencies showed no significant bias with mixture ratio; the range of $\sim \pm 1.5$ percent was representative of the precision of the instrumentation used.

## $H_2O_2$/MMH EVALUATION

Two $H_2O_2$/MMH test firings were made. The results are presented in Table 5

The first test was characterized by two pressure spikes approximately 13 milliseconds apart. The first spike was in excess of 3200 psi; the second was in excess of 2300 psi. Subsequent combustion was characterized by lower level spikes (approximately 400 psi) which had an average period of 1.2 milliseconds and persisted during the entire test. The test resulted in severe outward (upstream from the combustion chamber) bowing of the injector and inward bowing of the splash plate. The bowing resulted in the unseating of the sealing O-ring and subsequent gas leakage between injector and splash plate.

The second test was conducted with a new splash plate and injector. This test was characterized by one pressure spike in excess of 3400 psi. Low-level spikes of approximately the same amplitude and duration as in the first test occurred. Additionally the injector and splash plate were bowed as before and the O-ring was unseated.

## Oxidizer Leads

Based on the results of the $N_2O_4$/MMH tests, the differences between the oxidizer and fuel manifold fill times for the first and second $H_2O_2$/MMH tests were estimated to be +6.8 and +6.2 milliseconds, respectively. The measured mechanical oxidizer leads (times between oxidizer valve full-open position and fuel valve full-open position) were +34.8 and +5.2 milliseconds for the two tests. Subtracting the fill time differences from the mechanical leads resulted in true oxidizer leads of +28.0 and -1.0 milliseconds for introduction of propellant to the chamber.

## Ignition Delay

For the first $H_2O_2$/MMH run, a +34.8-millisecond mechanical oxidizer lead which corresponded to a +28.0-millisecond oxidizer lead to the chamber was employed (Table 5). Since there was an oxidizer lead at the chamber, the 22.9 milliseconds found for the time between fuel valve full open and chamber pressure rise corresponded to the sum of the fuel manifold fill time and ignition delay. Based on the $N_2O_4$/MMH data, if the two propellant systems had the same ignition delay, the time between fuel valve full open and chamber pressure rise for the $H_2O_2$/MMH test would have been approximately 12.9 milliseconds. Thus, the difference between 22.9 and 12.9 milliseconds or 10.0 milliseconds, approximately represents the increase in ignition delay for the $H_2O_2$/MMH run over the $N_2O_4$/MMH data.

For the second $H_2O_2$/MMH run, a +5.2 millisecond mechanical oxidizer lead which corresponded to a -1.0 millisecond oxidizer propellant lead to the chamber was employed. It was found that there was a 21.8 +5.2 millisecond (27.0 millisecond) interval between full-open position on the oxidizer valve and chamber pressure rise. Since there was a fuel lead to the chamber, the latter number corresponds to the sum of the oxidizer manifold fill time and ignition delay. Again, based on the $N_2O_4$/MMH data, if the two systems had the same ignition delay, the time between oxidizer valve full open position and chamber pressure rise for the $H_2O_2$/MMH test would have been approximately 19.4 milliseconds. The difference between 27.0 and 19.4 milliseconds (7.6 milliseconds) approximately represents the increase in ignition delay for the second $H_2O_2$/MMH run over the average for the $N_2O_4$/MMH system.

## CONCLUDING REMARKS

Under the experimental conditions of the present study, the ignition characteristics of the $N_2O_4$/MMH propellant combination were found to be far superior to those of the 98 wt. % $H_2O_2$/MMH propellant combination. The average ignition spike value for the 114 $N_2O_4$/MMH firings was 325 psi. For the two firings with the $H_2O_2$/MMH propellants, pressure spikes in the range of 3000 psi were found. The latter were of sufficient magnitude to substantially damage the injectors employed.

At the nominal mixture ratio of 2.0, an uncorrected efficiency of $94.1^{+1.6}_{-1.3}$ percent was found for the $N_2O_4$/MMH propellant combination. Because of the injector damage and resulting gas leakage between the injector and combustion chamber, as well as an unstable combustion condition, the c* efficiency was not measurable with the $H_2O_2$/MMH propellant combination.

The $N_2O_4$/MMH data were analyzed for the effect of valve timing on spiking magnitude. A maximum in spiking values was found for an approximately 5 milliseconds oxidizer lead (at the injector face). For the $N_2O_4$/MMH data, no correlation between spiking magnitudes and the estimated variations in ignition delay was found. The variations were estimated to be a maximum of ±0.9 millisecond. No absolute measurements of ignition delay were made. The average sums of the manifold fill time and ignition delay were 13.5 and 20.0 milliseconds for fuel and oxidizer, respectively. Ignition delays for the $H_2O_2$/MMH system were estimated to be 8 to 10 milliseconds greater than for the $N_2O_4$/MMH system.

## REFERENCES


1. R-7060-1, A Study of Ignition Pressure Spiking in Altitude Control Engines, Volume I, Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, May 1967.
2. R-2094P, Summary Report, Research Program on Hydrogen Peroxide, Contract NOas 56-1052d, Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 1 March 1960, CONFIDENTIAL.
3. RR 60-27, An Experimental Investigation of the Pentaborane/Hydrogen Peroxide Propellant Combination, by M. M. Berman and C. A. Younts, Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 6 January 1961, CONFIDENTIAL.

TABLE 1

TABULATION OF MEASURED PARAMETERS AND INSTRUMENTATION

| Measurement | Steady-State or Transient | Location | Instrument | Recorder |
|---|---|---|---|---|
| Flow | Steady-State | Fuel Line | Turbine Meter | Osc |
| Flow | Transient | Fuel Line | Vane Meter | T and Osc |
| Flow | Steady-State | Oxidant Line | Turbine Meter | Osc |
| Flow | Transient | Oxidant Line | Vane Meter | T and Osc |
| Temperature | Steady-State | Fuel Line | Thermocouple | Dyn and OF |
| Temperature | Steady-State | Oxidant Line | Thermocouple | Dyn and OF |
| Temperature | Steady-State | Fuel Storage | Thermocouple | Dyn |
| Temperature | Steady-State | Oxidant Storage | Thermocouple | Dyn |
| Temperature | Steady-State | Chamber Wall | Thermocouple | Dyn |
| Pressure | Steady-State | Oxidant Tank | Statham | Dyn |
| Pressure | Steady-State | Fuel Tank | Statham | Dyn |
| Pressure | Steady-State | Oxidant Line | Statham | OF and Osc |
| Pressure | Steady-State | Fuel Line | Statham | OF and Osc |
| Pressure | Steady-State | Injector | Statham | OF and Osc |
| Pressure | Transient | Nozzle | Kistler | T |
| Pressure | Transient | Nozzle | Kistler | T |
| Pressure | Transient | Chamber | Kistler | T and Scope |
| Pressure | Steady-State | Vacuum Tank | Baratron | Dyn and OF |
| Valve Signature | Transient | Fuel Line | | Osc, Scope |
| Valve Signature | Transient | Oxidizer Line | | Osc, Scope |
| Valve Signal | Transient | Fuel Line | | Osc |
| Valve Signal | Transient | Oxidizer Line | | Osc |

Notes:
Osc - Oscillograph
T - F-M Tape 0-20KC
Dyn - Dynalog Charts
Scope - Oscilloscope
OF - Beckman Offner

TABLE 2

SUMMARY OF $N_2O_4$/MMH TEST DATA

| Test No. | Propellant Temperature, F | Chamber Temperature, F | Ambient Pressure Prior to Test, mm Hg | Mechanical Oxidizer Lead (valve full open), milliseconds | Time From Oxidizer Valve Full Open Position to Chamber Pressure Rise, milliseconds | Time From Fuel Valve Full Open Position to Chamber Pressure Rise, milliseconds | Calculated Oxidizer Lead (introduction to chamber), milliseconds | $P_s/P_c$ |
|---|---|---|---|---|---|---|---|---|
| 247 | 82/90 | 101 | 0.72 | +17.4 | θ | θ | +10.9 | θ |
| 248 | 84/91 | 105 | 0.85 | +16.4 | 29.4 | 13.0 | + 9.9 | 1.33 |
| 249 | 84/91 | 108 | 1.00 | +16.7 | 30.1 | 13.4 | +10.2 | 1.36 |
| 250 | 85/93 | 109 | 1.10 | +16.5 | 29.9 | 13.4 | +10.0 | 1.58 |
| 251 | 86/93 | 110 | 1.25 | +26.8 | 40.4 | 13.6 | +20.3 | 1.77 |
| 252 | 86/95 | 110 | 1.50 | +17.0 | 30.4 | 13.4 | +10.5 | 1.88 |
| 253 | 92/101 | 101 | 0.52 | +19.2 | 32.2 | 13.0 | +12.7 | 1.62 |
| 254 | 92/101 | 102 | 0.70 | +19.6 | 33.1 | 13.5 | +13.1 | 1.63 |
| 255 | 92/100 | 103 | 0.72 | +20.3 | 33.7 | 13.4 | +13.8 | 1.55 |
| 256 | 92/100 | 103 | 0.80 | +19.3 | 32.6 | 13.3 | +12.8 | 1.94 |
| 257 | 95/103 | 103 | 0.90 | +19.3 | 32.3 | 13.1 | +12.8 | 1.82 |
| 258 | 96/104 | 102 | 0.92 | +19.3 | 32.8 | 13.5 | +12.8 | 1.62 |
| 259 | 96/103 | 102 | 0.90 | +20.4 | 34.1 | 13.7 | +13.9 | 1.87 |
| 260 | 96/104 | 102 | 0.50 | +19.2 | 32.8 | 13.6 | +12.7 | 1.69 |
| 261 | 95/102 | 102 | 0.52 | +19.2 | 32.8 | 13.6 | +12.7 | 1.53 |
| 262 | 94/102 | 101 | 0.65 | +19.3 | 32.6 | 13.3 | +12.8 | 1.58 |
| 263 | 91/102 | 101 | 0.78 | +20.3 | 33.5 | 13.2 | +13.8 | 1.84 |
| 264 | 94/103 | 101 | 0.69 | +22.1 | 35.9 | 13.8 | +15.6 | 1.35 |
| 265 | 87/102 | 102 | 0.79 | +22.4 | 35.8 | 13.4 | +15.9 | 1.73 |
| 266 | 89/104 | 102 | 0.80 | +22.5 | 36.2 | 13.7 | +16.0 | 1.67 |
| 267 | 96/103 | 102 | 1.02 | +21.7 | 35.1 | 13.4 | +15.2 | 1.76 |
| 268 | 97/106 | 102 | 0.29 | +22.0 | 26.1 | 14.1 | +15.5 | 1.64 |
| 269 | 91/107 | 103 | 0.40 | +22.0 | 25.7 | 13.7 | +15.5 | 2.12 |
| 270 | 94/107 | 103 | 0.55 | +21.8 | 35.4 | 13.6 | +15.3 | 1.69 |
| 271 | 96/107 | 102 | 0.68 | +20.9 | 34.6 | 13.7 | +14.4 | 1.88 |
| 272 | 92/106 | 102 | 0.50 | +20.7 | 34.4 | 13.7 | +14.2 | 1.83 |
| 273 | 95/106 | 102 | 0.71 | +20.4 | 34.1 | 13.7 | +13.9 | 1.78 |
| 274 | 89/102 | 102 | 1.07 | +20.0 | 33.2 | 13.2 | +13.5 | 1.67 |
| 275 | 91/102 | 102 | 0.50 | +19.5 | 32.7 | 13.2 | +13.0 | 1.57 |
| 276 | 92/103 | 102 | 0.70 | +20.6 | 34.4 | 13.8 | +14.1 | 1.65 |
| 277 | 93/103 | 101 | 0.80 | +20.6 | 34.2 | 13.6 | +14.1 | 1.74 |

TABLE 2

(Continued)

| Test No. | Propellant Temperature, F | Chamber Temperature, F | Ambient Pressure Prior to Test, mm Hg | Mechanical Oxidizer Lead (valve full open), milliseconds | Time From Oxidizer Valve Full Open Position to Chamber Pressure Rise, milliseconds | Time From Fuel Valve Full Open Position to Chamber Pressure Rise, milliseconds | Calculated Oxidizer Lead (introduction to chamber), milliseconds | $P_s/P_c$ |
|---|---|---|---|---|---|---|---|---|
| 278 | 93/102 | 101 | 0.80 | +20.3 | 34.0 | 13.7 | +13.8 | 2.00 |
| 279 | 93/102 | 101 | 0.82 | +20.7 | 34.3 | 13.6 | +14.2 | 1.71 |
| 280 | 94/102 | 102 | 0.88 | — | — | — | θ | θ |
| 281 | 92/100 | 102 | 0.89 | +20.0 | 33.2 | 13.2 | +13.5 | 1.65 |
| 282 | 93/101 | 102 | 1.00 | +20.9 | 33.9 | 13.0 | +14.4 | 14.30 |
| 283 | 96/104 | 102 | 0.44 | +33.4 | 46.8 | 13.4 | +26.9 | 1.26 |
| 284 | 96/104 | 102 | 0.53 | +12.0 | 25.4 | 13.4 | + 5.5 | 1.59 |
| 285 | 96/103 | 102 | 0.74 | +31.8 | 45.8 | 14.0 | +25.3 | 1.19 |
| 286 | 95/103 | 102 | 0.82 | +12.2 | 25.3 | 13.1 | + 5.7 | 6.55 |
| 287 | 95/102 | 100 | 0.88 | +31.8 | 45.8 | 14.0 | +25.3 | 1.18 |
| 288 | 95/102 | 102 | 0.89 | +11.9 | 25.2 | 13.3 | + 5.4 | 6.13 |
| 289 | 92/102 | 102 | 0.90 | +30.9 | 44.5 | 14.5 | +24.4 | 1.26 |
| 290 | 93/102 | 101 | 1.03 | +11.3 | 24.6 | 13.3 | + 4.8 | 3.19 |
| 291 | 97/105 | 102 | 0.32 | +31.2 | 45.0 | 13.8 | +24.7 | 1.17 |
| 292 | 96/105 | 101 | 0.60 | +11.7 | 24.8 | 13.1 | + 5.2 | 1.68 |
| 293 | 97/104 | 102 | 0.52 | +31.4 | 45.8 | 14.4 | +24.9 | 1.68 |
| 294 | 95/103 | 101 | 0.70 | +11.7 | 25.3 | 13.6 | + 5.2 | 2.16 |
| 295 | 96/104 | 102 | 0.75 | +31.0 | 44.5 | 13.5 | +24.5 | 2.78 |
| 296 | 94/103 | 102 | 0.80 | +10.9 | 24.9 | 14.0 | + 4.4 | 1.15 |
| 297 | 94/101 | 102 | 0.95 | +31.3 | 45.6 | 14.3 | +24.8 | 1.33 |
| 298 | 96/104 | 102 | 1.00 | +11.8 | 26.1 | 14.3 | + 5.3 | 1.48 |
| 299 | 95/104 | 102 | 0.50 | +31.0 | 44.6 | 13.6 | +24.5 | 1.86 |
| 300 | 95/104 | 103 | 0.75 | +11.9 | 25.5 | 13.6 | + 5.4 | 24.30 |
| 301 | 94/103 | 102 | 2.00 | +21.0 | 34.4 | 13.4 | +14.5 | 1.80 |
| 302 | 94/103 | 102 | 0.74 | +11.8 | 25.2 | 13.4 | + 5.3 | 1.96 |
| 303 | 94/102 | 102 | 0.95 | +30.7 | 44.1 | 13.4 | +24.2 | 1.78 |
| 304 | 95/103 | 103 | 0.80 | - 2.2 | 16.6 | 18.8 | - 8.7 | 1.92 |
| 305 | 93/102 | 102 | 0.60 | -27.3 | 22.0 | 49.3 | -33.8 | 1.06 |
| 306 | 95/105 | 101 | 0.62 | -29.4 | 22.3 | 51.7 | -35.9 | 1.10 |
| 307 | 98/108 | 102 | 0.75 | -30.7 | 21.9 | 52.6 | -37.2 | 1.33 |
| 308 | 97/105 | 101 | 0.80 | +30.9 | 44.9 | 14.0 | +24.4 | 1.81 |
| 309 | 97/105 | 102 | 1.00 | +30.8 | 44.2 | 13.4 | +24.3 | 3.22 |
| 310 | 94/103 | 101 | 0.60 | + 8.4 | 22.6 | 14.2 | + 1.9 | 1.32 |
| 311 | 94/103 | 102 | 0.74 | - 4.7 | 20.4 | 25.1 | -11.2 | 1.25 |
| 312 | 92/103 | 102 | 0.92 | - 4.3 | 20.4 | 24.7 | -10.8 | 1.10 |
| 313 | 92/102 | 102 | 1.00 | - 3.0 | 20.6 | 23.6 | - 9.5 | 1.11 |
| 314 | 93/104 | 102 | 0.60 | - 3.1 | 21.1 | 24.4 | - 9.6 | 1.18 |
| 315 | 90/102 | 102 | 0.90 | - 3.0 | 20.1 | 23.1 | - 9.5 | 1.13 |

# TABLE 2
## (Continued)

| Test No. | Propellant Temperature, F | Chamber Temperature, F | Ambient Pressure Prior to Test, mm Hg | Mechanical Oxidizer Lead (valve full open), milliseconds | Time From Oxidizer Valve Full Open Position to Chamber Pressure Rise, milliseconds | Time From Fuel Valve Full Open Position to Chamber Pressure Rise, milliseconds | Calculated Oxidizer Lead (introduction to chamber), milliseconds | $P_s/P_c$ |
|---|---|---|---|---|---|---|---|---|
| 316 | 90/100 | 103 | 0.80 | - 1.8 | 20.2 | 22.0 | - 8.3 | 1.45 |
| 317 | 88/ 99 | 101 | 1.00 | - 2.4 | 20.0 | 22.4 | - 8.9 | 1.24 |
| 318 | 87/98 | 102 | 1.00 | - 3.3 | 20.1 | 23.4 | - 9.8 | 1.33 |
| 319 | 92/101 | 102 | 1.00 | - 1.8 | 20.0 | 21.8 | - 8.3 | 1.32 |
| 320 | 95/102 | 101 | 0.60 | - 2.4 | 20.5 | 22.9 | - 8.9 | 1.23 |
| 321 | 94/104 | 101 | 0.80 | - 2.0 | 20.4 | 22.4 | - 8.5 | 1.24 |
| 322 | 94/103 | 100 | 0.95 | - 1.7 | 20.5 | 22.2 | - 8.2 | 1.34 |
| 323 | 93/103 | 101 | 0.85 | - 2.1 | 20.6 | 22.7 | - 8.6 | 1.20 |
| 324 | 95/103 | 102 | 0.67 | + 9.7 | 23.5 | 13.8 | + 3.2 | 1.92 |
| 325 | 95/104 | 102 | 0.74 | + 8.3 | 21.5 | 13.2 | + 1.8 | 2.07 |
| 326 | 94/103 | 101 | 0.84 | + 8.0 | 21.2 | 13.2 | + 1.5 | 2.81 |
| 327 | 94/102 | 101 | 0.88 | + 8.0 | 21.0 | 13.0 | + 1.5 | 2.94 |
| 328 | 95/102 | 102 | 0.78 | + 8.0 | 21.1 | 13.1 | + 1.5 | 2.78 |
| 329 | 96/103 | 102 | 0.87 | + 8.0 | 21.1 | 13.1 | + 1.5 | 3.11 |
| 330 | 95/103 | 102 | 1.00 | + 8.1 | 21.4 | 13.3 | + 1.6 | 3.77 |
| 331 | 95/102 | 102 | 1.02 | + 8.2 | 21.4 | 13.2 | + 1.7 | 3.03 |
| 332 | 98/105 | 102 | 0.77 | + 8.0 | 21.4 | 13.4 | + 1.5 | 1.74 |
| 333 | 97/105 | 102 | 0.72 | + 8.3 | 21.8 | 13.5 | + 1.8 | 2.86 |
| 334 | 96/104 | 102 | 0.73 | + 8.0 | 21.2 | 13.2 | + 1.5 | 2.46 |
| 335 | 97/104 | 102 | 0.81 | + 7.8 | 21.2 | 13.4 | + 1.3 | 1.84 |
| 336 | 95/104 | 102 | 1.00 | + 8.1 | 21.5 | 13.4 | + 1.6 | 1.65 |
| 337 | 95/103 | 102 | 0.96 | + 8.1 | 21.6 | 13.5 | + 1.6 | 2.23 |
| 338 | 95/103 | 102 | 1.00 | + 7.9 | 21.2 | 13.3 | + 1.4 | 2.09 |
| 339 | 96/103 | 102 | 1.03 | + 7.6 | 21.2 | 13.6 | + 1.1 | 1.79 |
| 340 | 96/103 | 102 | 1.04 | + 7.3 | 20.7 | 13.4 | + 0.8 | 1.42 |
| 341 | 97/104 | 102 | 0.44 | - 1.3 | 20.0 | 21.3 | - 7.8 | 1.25 |
| 342 | 96/102 | 102 | 0.62 | - 1.5 | 19.9 | 21.4 | - 8.0 | 1.29 |
| 343 | 95/102 | 101 | 0.75 | - 1.3 | 20.0 | 21.3 | - 7.8 | 1.31 |
| 344 | 95/102 | 102 | 0.89 | - 1.2 | 20.0 | 21.2 | - 7.7 | 1.42 |
| 345 | 95/102 | 102 | 0.98 | - 1.3 | 20.0 | 21.3 | - 7.8 | 1.49 |
| 346 | 94/101 | 101 | 0.97 | - 1.3 | 19.8 | 21.1 | - 7.8 | 1.28 |
| 347 | 94/100 | 101 | 0.96 | - 1.3 | 19.3 | 20.6 | - 7.8 | 1.38 |

## TABLE 2
## (Concluded)

| Test No. | Propellant Temperature, F | Chamber Temperature, F | Ambient Pressure Prior to Test, mm Hg | Mechanical Oxidizer Lead (valve full open), milliseconds | Time From Oxidizer Valve Full Open Position to Chamber Pressure Rise, milliseconds | Time From Fuel Valve Full Open Position to Chamber Pressure Rise, milliseconds | Calculated Oxidizer Lead (introduction to chamber), milliseconds | $P_s/P_c$ |
|---|---|---|---|---|---|---|---|---|
| 348 | 94/100 | 102 | 1.02 | - 1.3 | 20.0 | 21.3 | - 7.8 | 1.26 |
| 349 | 94/100 | 102 | 1.03 | - 1.6 | 19.8 | 21.4 | - 8.1 | 1.37 |
| 350 | 94/101 | 102 | 0.64 | + 8.6 | 21.8 | 13.2 | + 2.1 | 2.22 |
| 351 | 94/101 | 102 | 0.97 | + 8.6 | 21.7 | 13.1 | + 2.1 | 3.88 |
| 352 | 94/101 | 101 | 0.98 | + 8.7 | 21.9 | 13.2 | + 2.2 | 1.60 |
| 353 | 94/100 | 101 | 1.02 | + 8.8 | 21.8 | 13.0 | + 2.3 | 1.80 |
| 354 | 94/100 | 101 | 1.02 | + 8.7 | 21.8 | 13.1 | + 2.2 | 2.04 |
| 355 | 94/101 | 102 | 1.04 | + 8.5 | 21.7 | 13.2 | + 2.0 | 1.87 |
| 356 | 93/100 | 101 | 1.05 | + 8.0 | 21.2 | 13.2 | + 1.5 | 1.84 |
| 357 | 94/101 | 103 | 0.74 | + 6.4 | 19.8 | 13.4 | - 0.1 | 1.93 |
| 358 | 95/102 | 104 | 0.97 | + 6.9 | 20.1 | 13.2 | + 0.4 | 2.98 |
| 359 | 94/101 | 103 | 1.03 | + 7.6 | 20.6 | 13.0 | + 1.1 | 2.26 |
| 360 | 94/100 | 103 | 1.03 | + 7.2 | 20.5 | 13.3 | + 0.7 | 2.12 |
| 361 | 94/101 | 103 | 1.02 | + 7.2 | 20.4 | 13.2 | + 0.7 | 2.12 |
| 362 | 94/101 | 103 | 1.02 | + 7.0 | 20.2 | 13.2 | + 0.5 | 1.93 |

NOTES:

| | |
|---|---|
| Propellant Temperature | Oxidizer Temperature, F/Fuel Temperature, F |
| Mechanical Oxidizer Lead | Time between oxidizer valve full open position and fuel valve full open position; determined from secondary coil induced voltage-time traces |
| Calculated Oxidizer Lead | Calculated value of oxidizer propellant lead at injector face (details presented in text) |
| $P_s/P_c$ | Ratio of maximum ignition to steady-state pressure |
| $\theta$ | Data not available due to lack of instrumentation |

TABLE 3

EFFECT OF VALVE TIMING ON AVERAGE SPIKE RATIO*

| Range of Oxidizer Leads, **milliseconds | Range of Spike Ratios* | Average Spike Ratio | Number of Tests in Range |
|---|---|---|---|
| +24.4 to +25.3 | 1.2 to 3.2 | 1.7 | 11 |
| +9.9 to +16.0 | 1.3 to 2.1 | 2.1 | 34 |
| +3.2 to +5.7 | 1.2 to 24.3 | 4.7 | 11 |
| +0.1 to +2.4 | 1.3 to 3.9 | 2.3 | 30 |
| -7.8 to -11.2 | 1.1 to 1.9 | 1.3 | 23 |
| -33.8 to -37.2 | 1.1 to 1.3 | 1.2 | 3 |

*Ratio of maximum to steady-state chamber pressure
**Actual oxidizer lead at injector face, milliseconds

TABLE 4

SUMMARY OF CHARACTERISTIC VELOCITY PERFORMANCE
FOR THE $N_2O_4$/MMH PROPELLANT COMBINATION

| Test No. | Total Flowrate, lb/sec | Chamber Pressure, psia | Mixture Ratio, o/f | c* Efficiency, percent |
|---|---|---|---|---|
| 252 | 0.358 | 150 | 1.91 | 94.4 |
| 263 | 0.352 | 145 | 1.93 | 93.0 |
| 281 | 0.344 | 146 | 1.92 | 95.7 |
| 301 | 0.352 | 144 | 2.03 | 92.8 |
| 323 | 0.347 | 145 | 1.92 | 94.2 |
| 340 | 0.347 | 143 | 1.99 | 93.5 |
| 362 | 0.351 | 147 | 2.13 | 95.4 |

# TABLE 5

## SUMMARY OF $H_2O_2$/MMH TEST DATA

| Test No. | Propellant Temperature, F | Chamber Temperature, F | Altitude, mm Hg | Mechanical Oxidizer Lead, milliseconds | Time From Oxidizer Valve Full Open Position to Chamber Pressure Rise, milliseconds | Time from Fuel Valve Full Open Position to Chamber Pressure Rise, milliseconds | Calculated Oxidizer Lead (introduction to chamber), milliseconds | $P_s$, psi |
|---|---|---|---|---|---|---|---|---|
| 363 | 113/95 | 109 | 1.0 | +34.8 | 53.7 | 22.9 | +28.0 | >3200, >2300 |
| 364 | 113/93 | 99 | 0.5 | + 5.2 | 27.0 | 21.8 | -1.0 | >3400 |

Notes:

| | |
|---|---|
| Propellant Temperature | Oxidizer Temperature, F/Fuel Temperature, F |
| Mechanical Oxidizer Lead | Time between oxidizer valve full open and fuel valve full open determined from secondary coil induced voltage-time traces |
| Calculated Oxidizer Lead | Calculated value of oxidizer propellant lead at injector face (details presented in text) |
| $P_s$ | The maximum or spiking pressure observed during ignition |

FOLDOUT FRAME 1

FOLDOUT FRAME 2

ROCKETDYNE • A DIVISION OF NORTH AMERICAN AVIATION, INC.

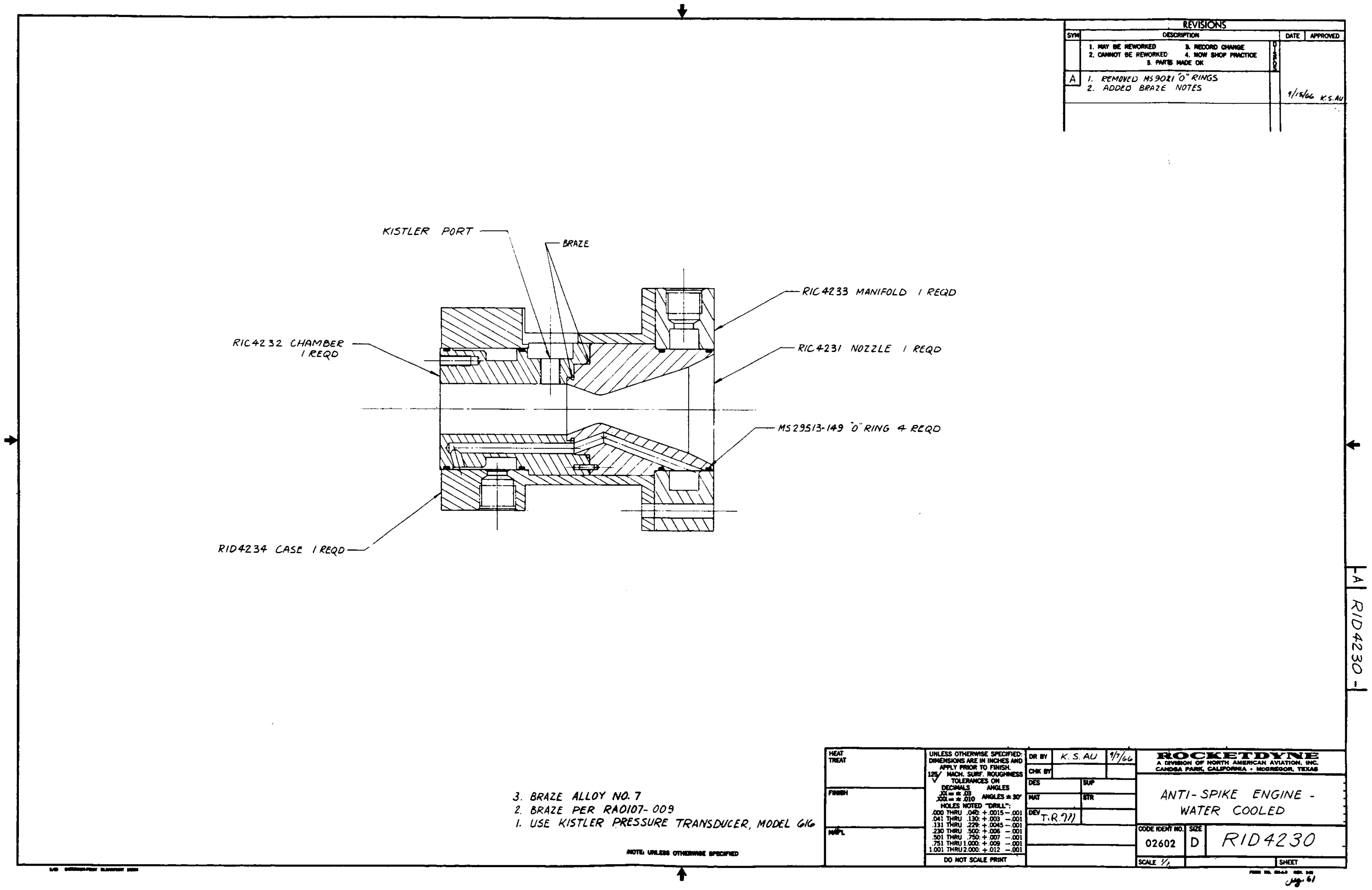
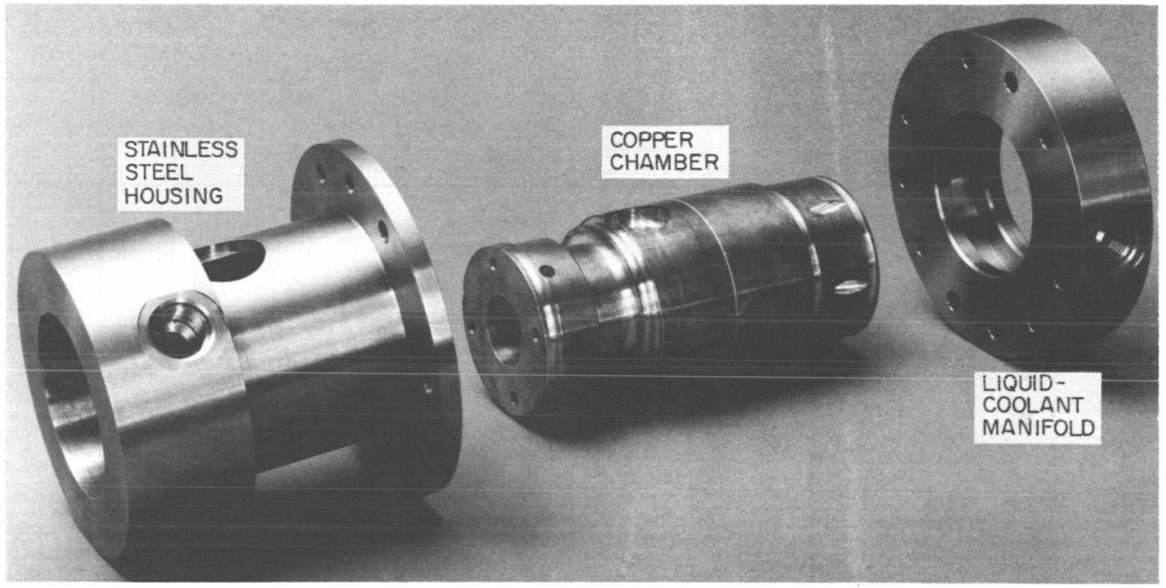
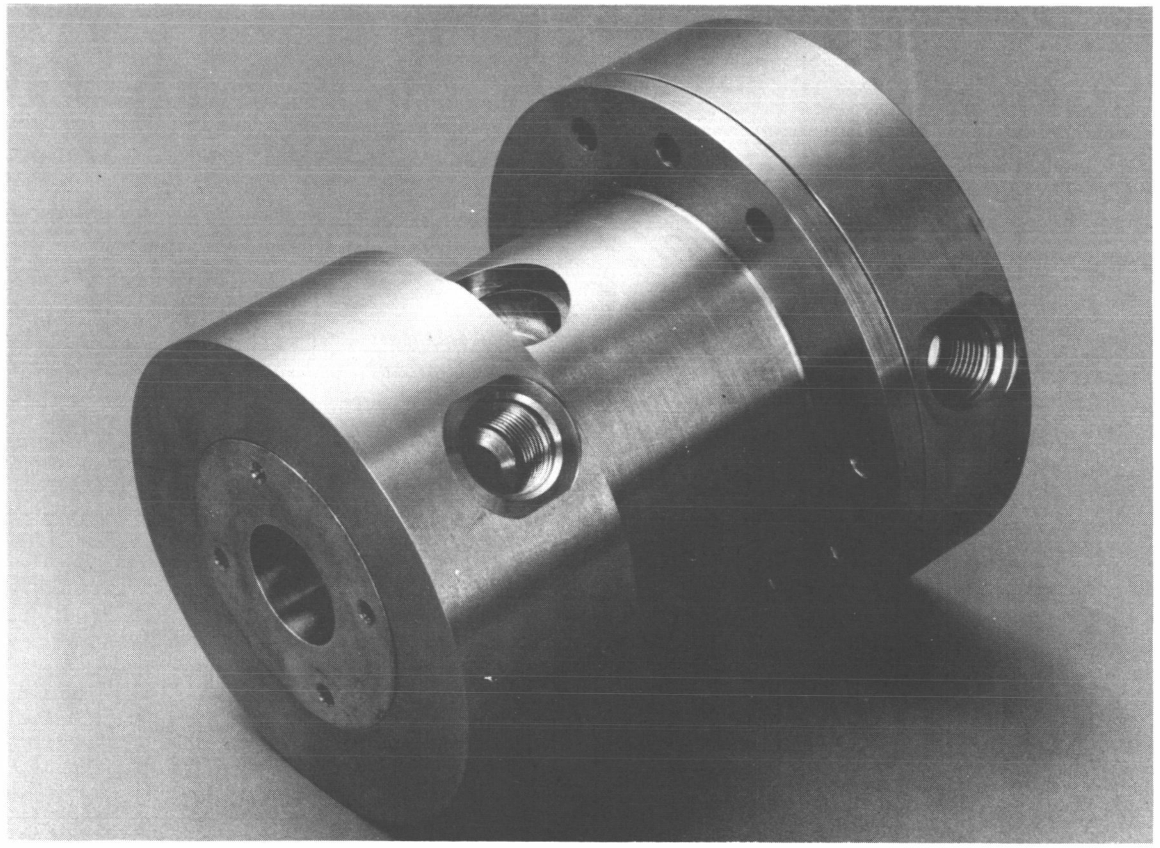



Figure 1. Anti-Spike Engine (Water Cooled)




1XW31-11/17/66-S1B



1XW31-11/17/66-S1A

Figure 2. Liquid-Cooled Combustion Chamber and Nozzle Assembly

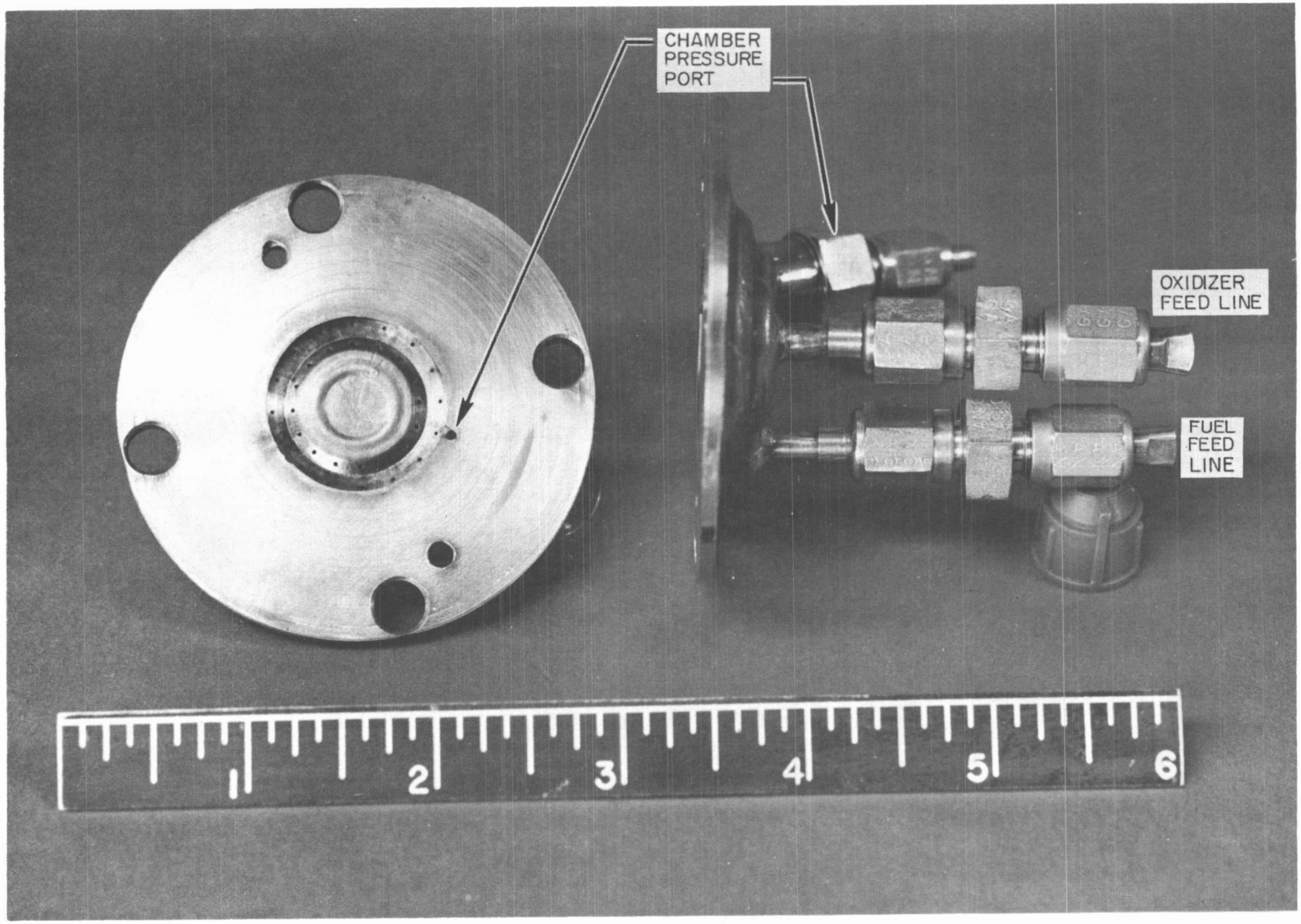



Figure 3. Sixteen Element Unlike Doublet Injector without Attached Splash Plate

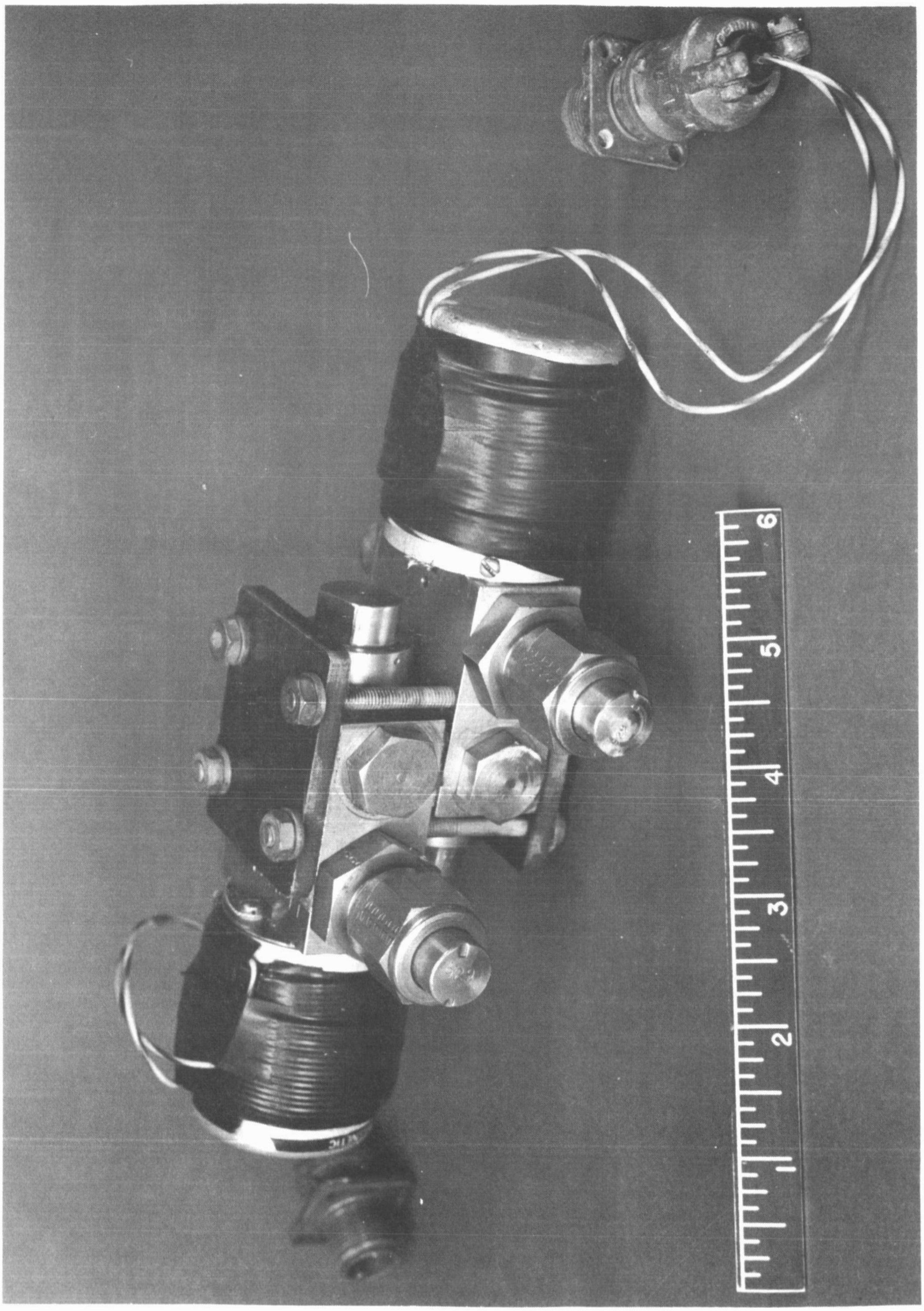


Figure 4. Main Propellant Valves Used for Both $N_2O_4$/MMH and $H_2O_2$/MMH Testing

FOLDOUT FRAME 1

FOLDOUT FRAME 2

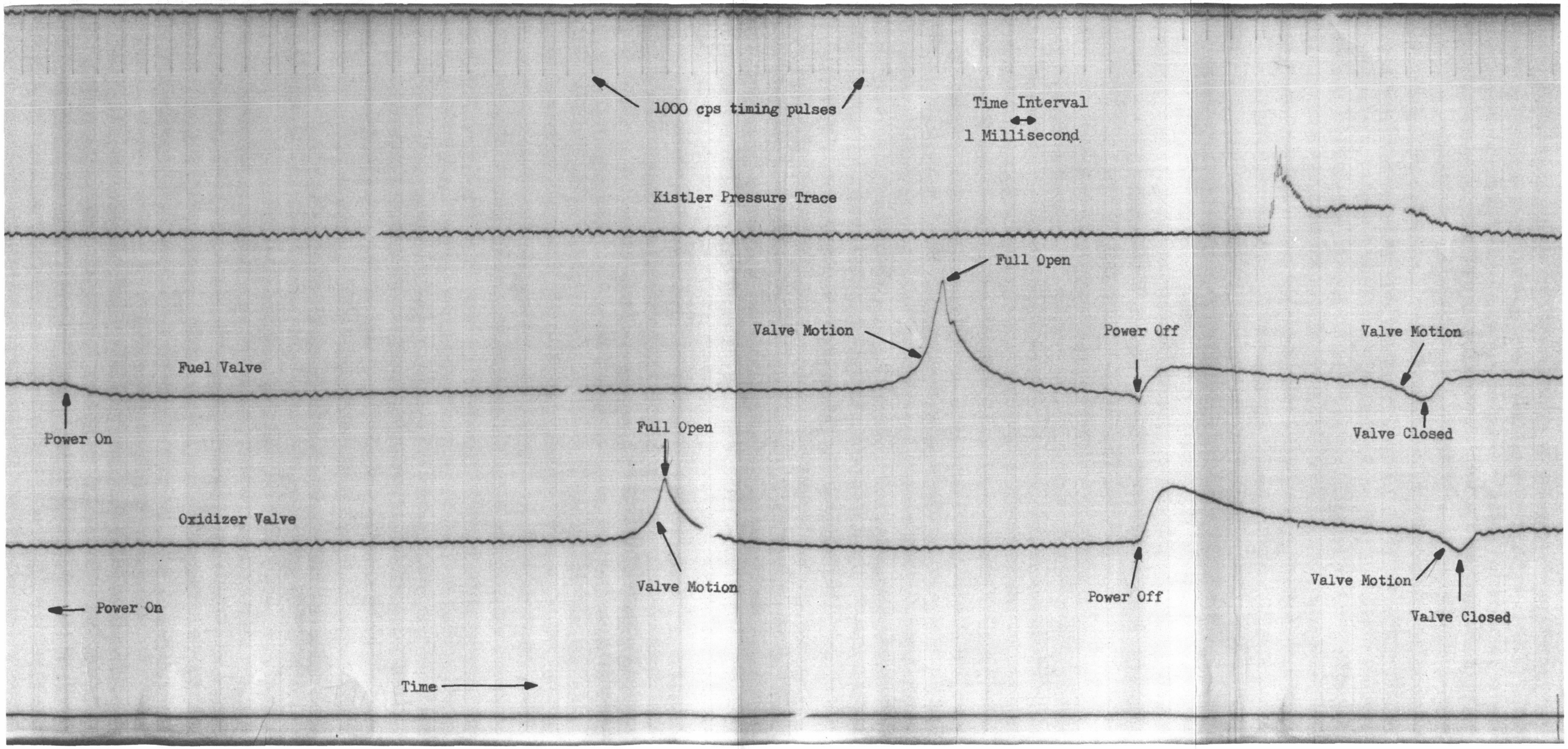



Figure 5. Valve and Kistler Pressure Transducer Traces (Run 290)

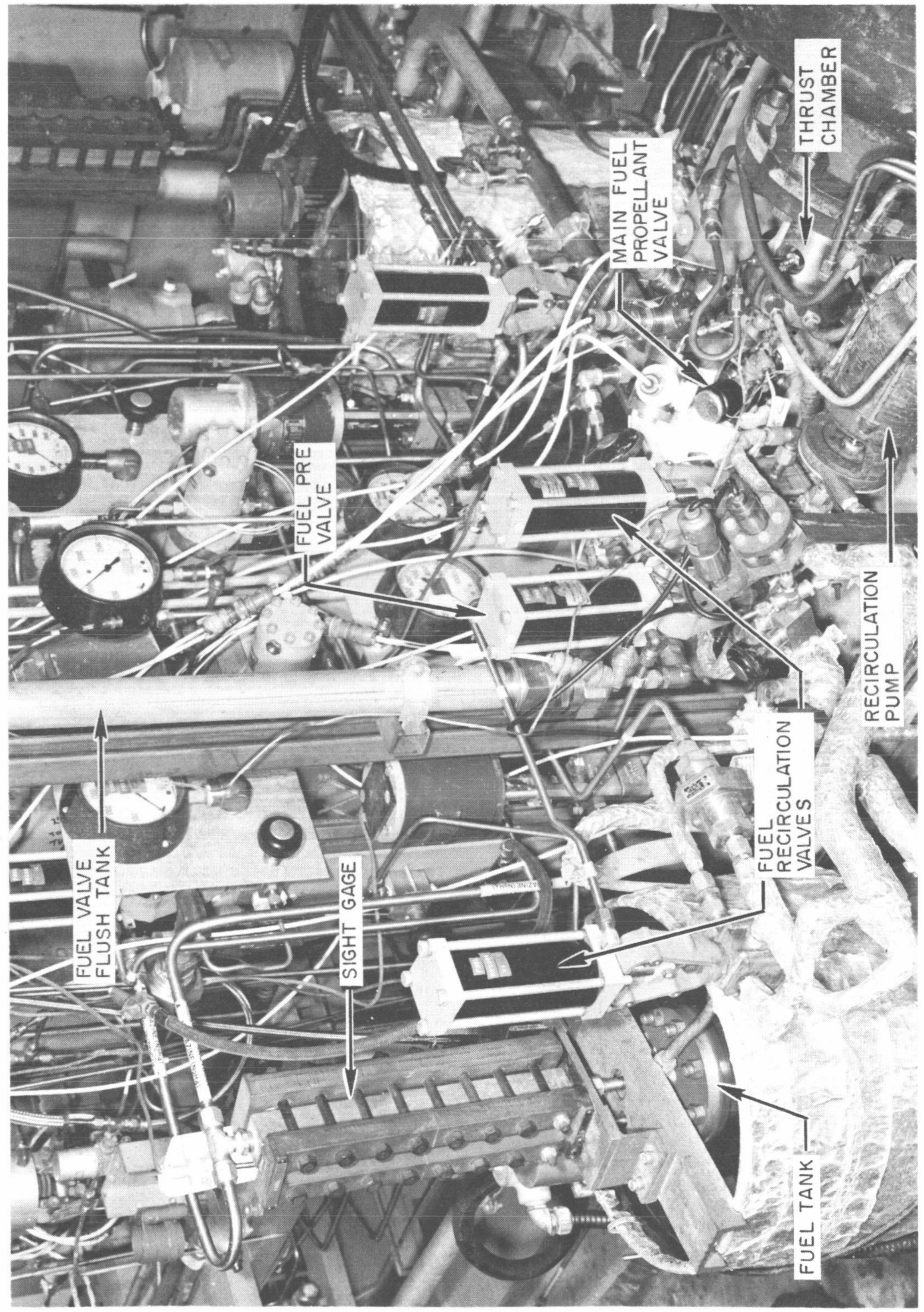



Figure 6. Propellant Feed Systems and Test Stand

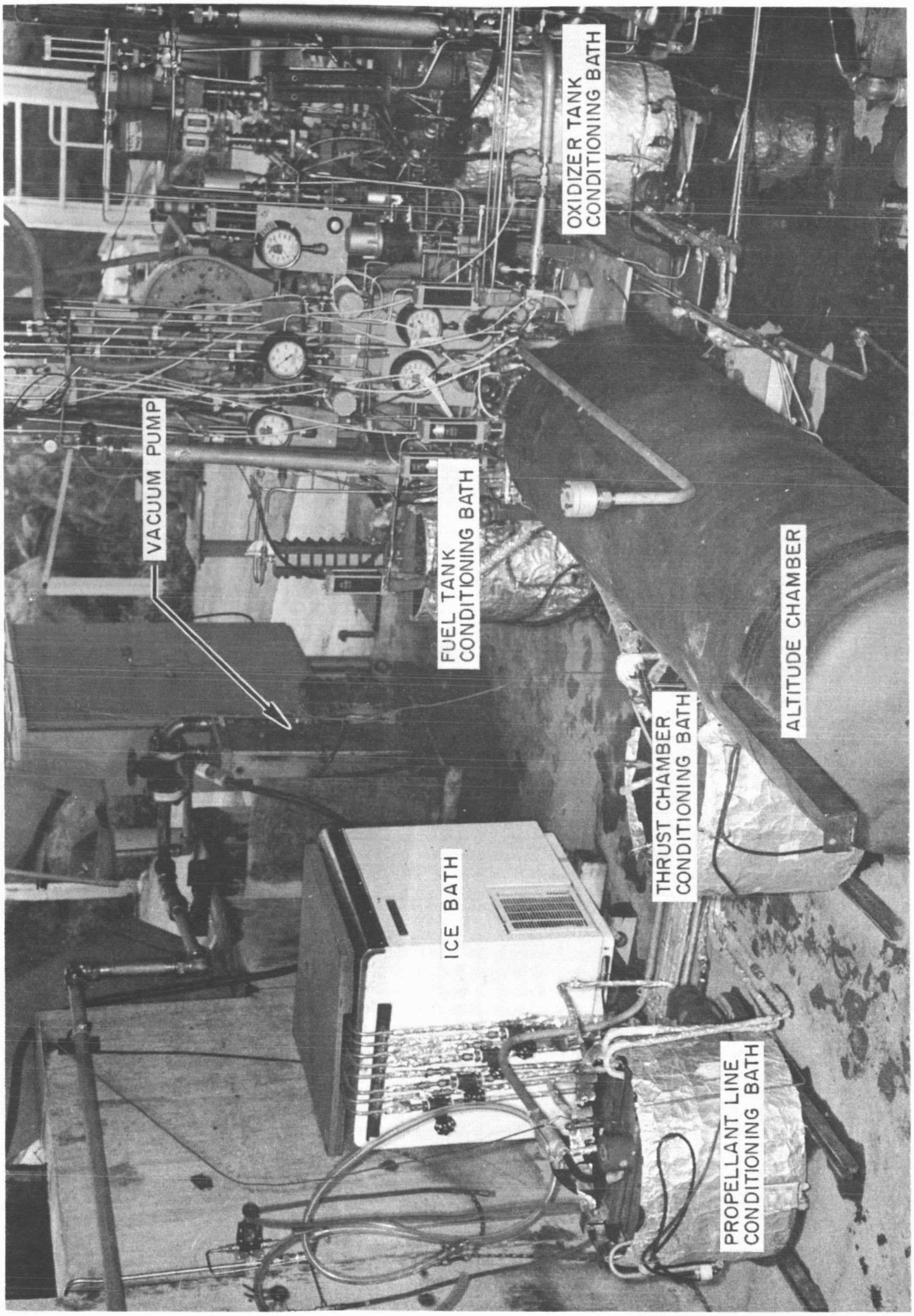



Figure 7. Conditioning System, Vacuum System and Chamber, and Test Stand

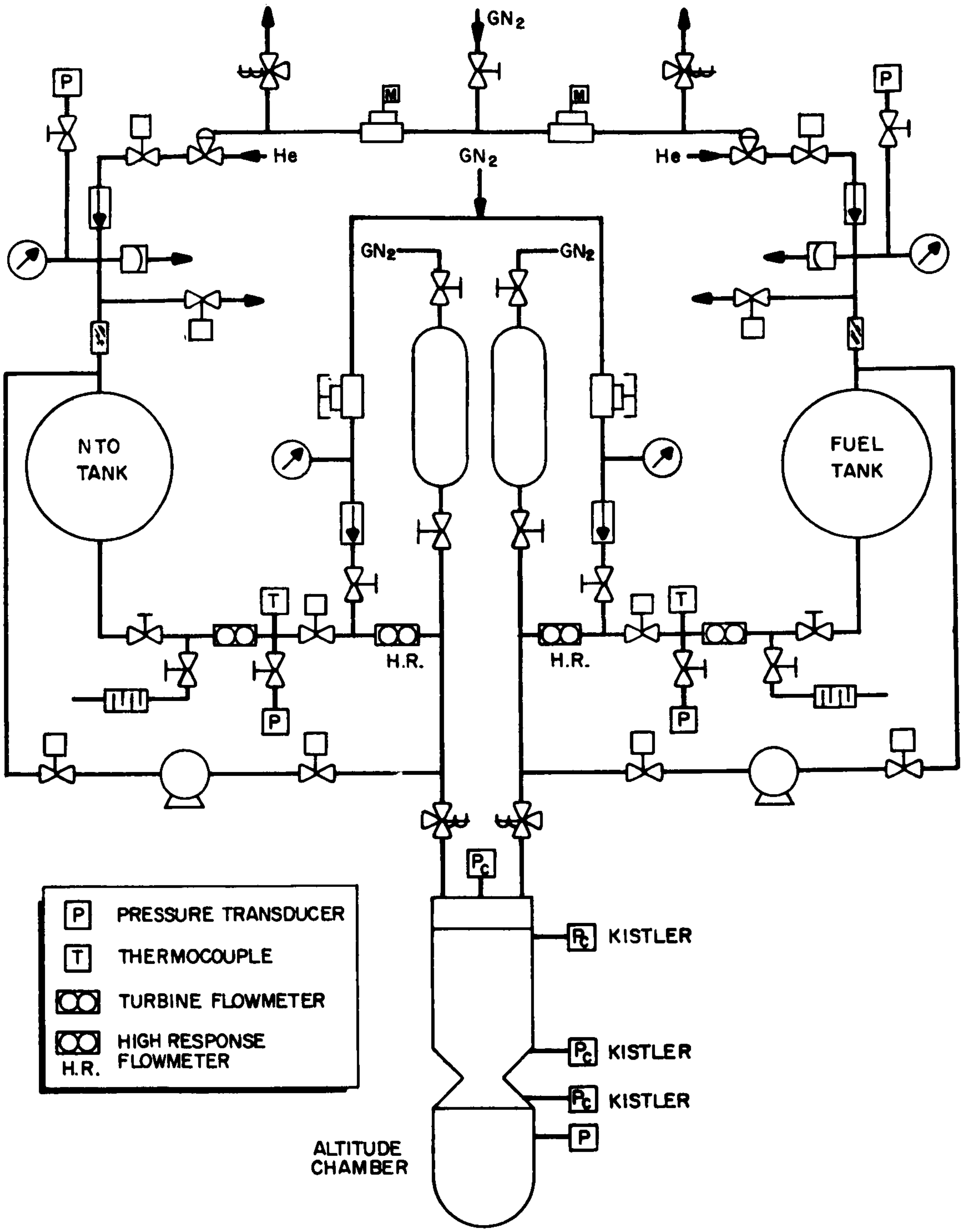



Figure 8. Schematic Representation of the Propellant Feed Systems and Test Engine Used for $N_2O_4$/Hydrazine-Type Fuel Tests

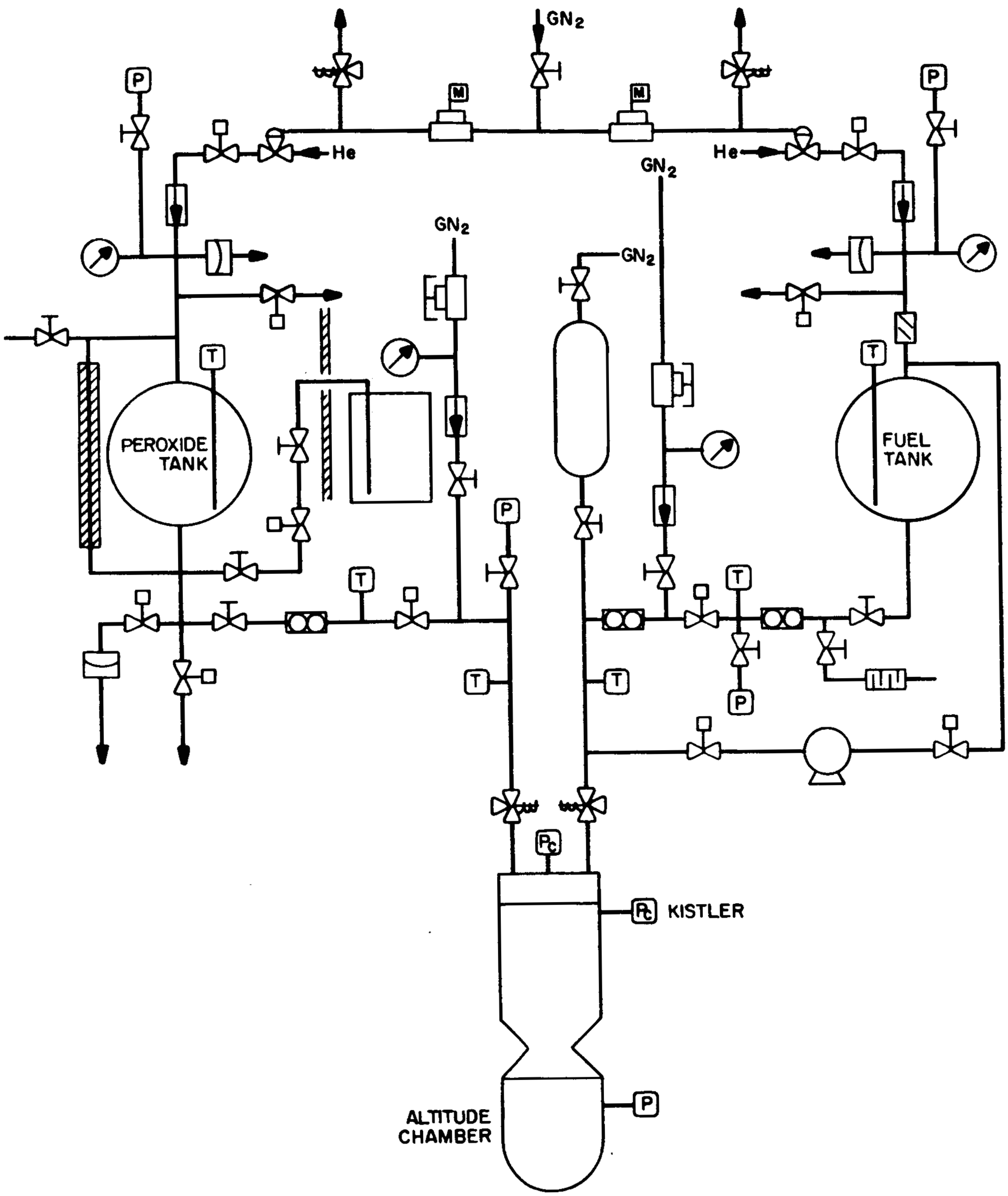



Figure 9. Schematic Representation of Propellant Feed Systems and Test Engine Used for $H_2O_2$/MMH Tests

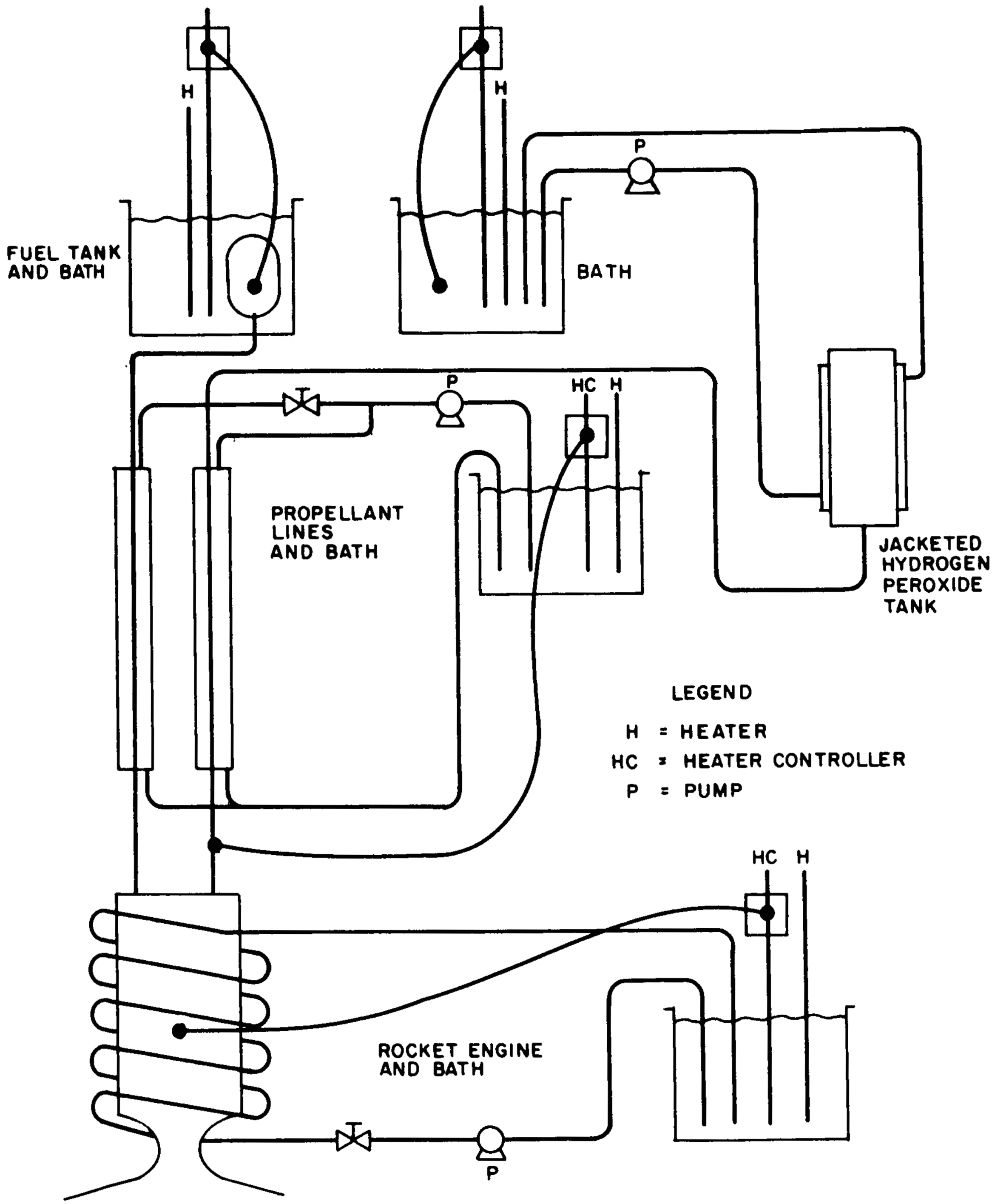



Figure 10. Schematic Representation of the Temperature Conditioning System Used for the Hydrogen Peroxide/MMH Tests

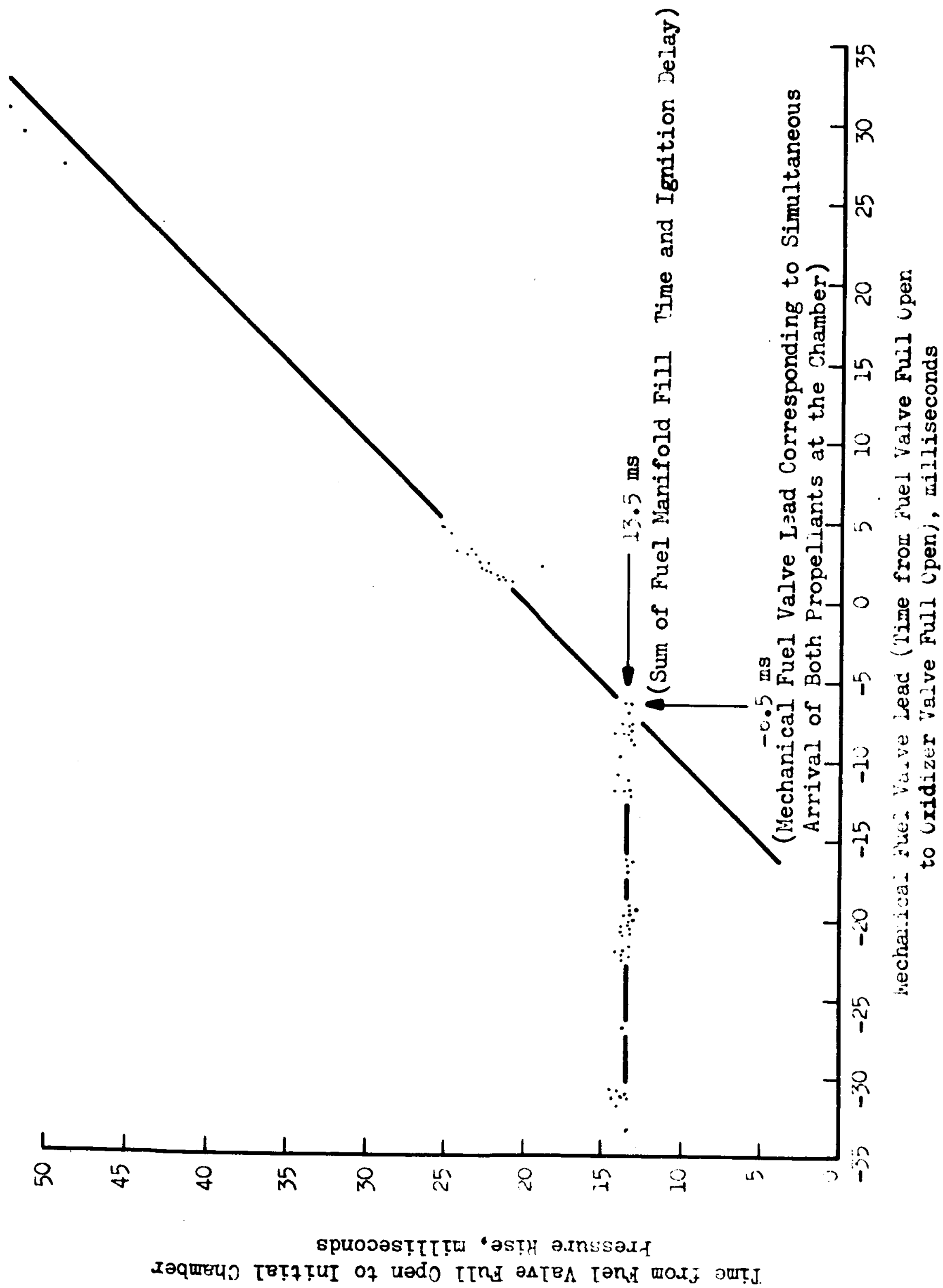



Figure 11. Graphical Determination of Propellant Lead-Lag Relationships for $N_2O_4$/MMH

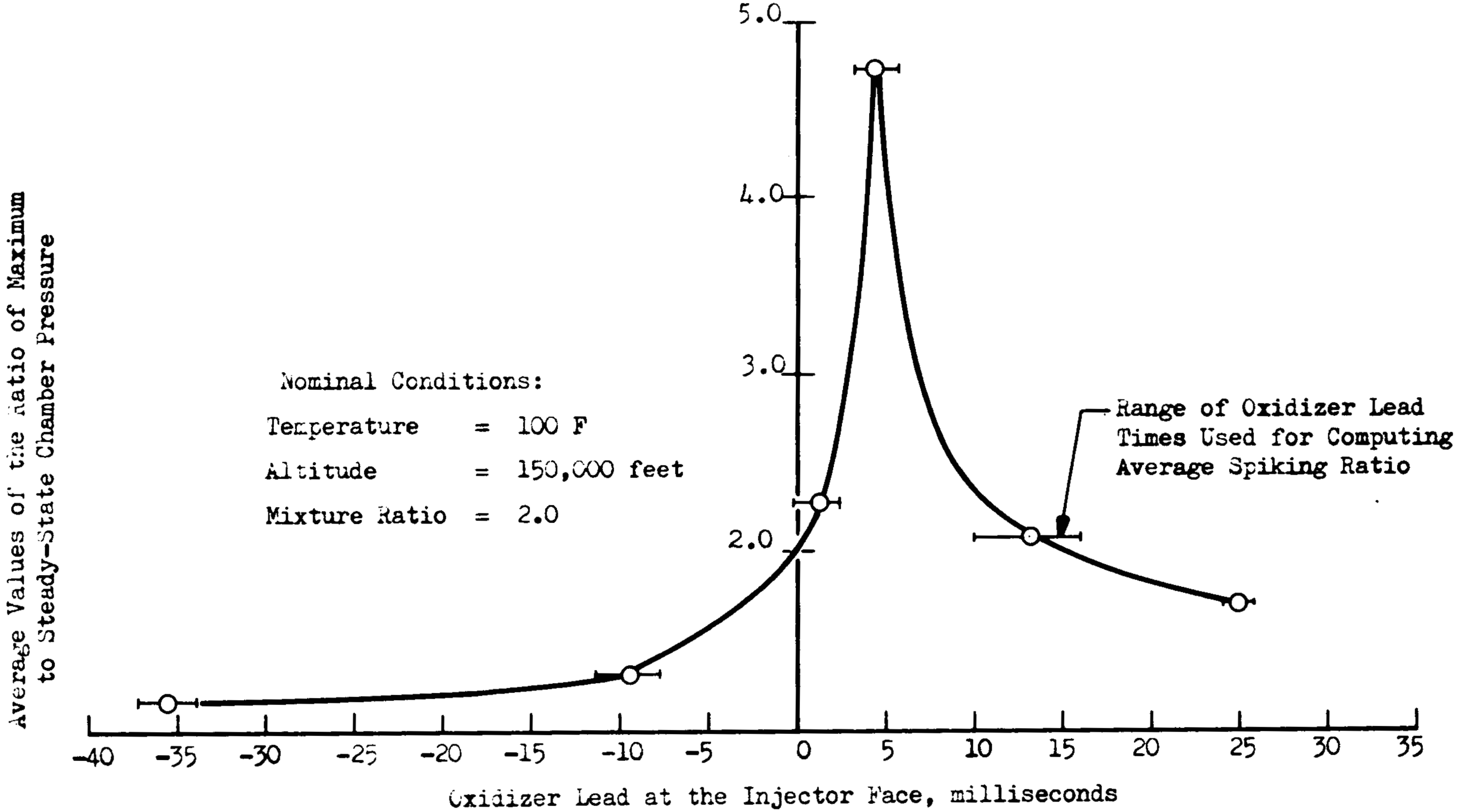



Figure 12. Variation of $N_2O_4$/MMH Spiking Characteristics with Oxidizer Lead Conditions

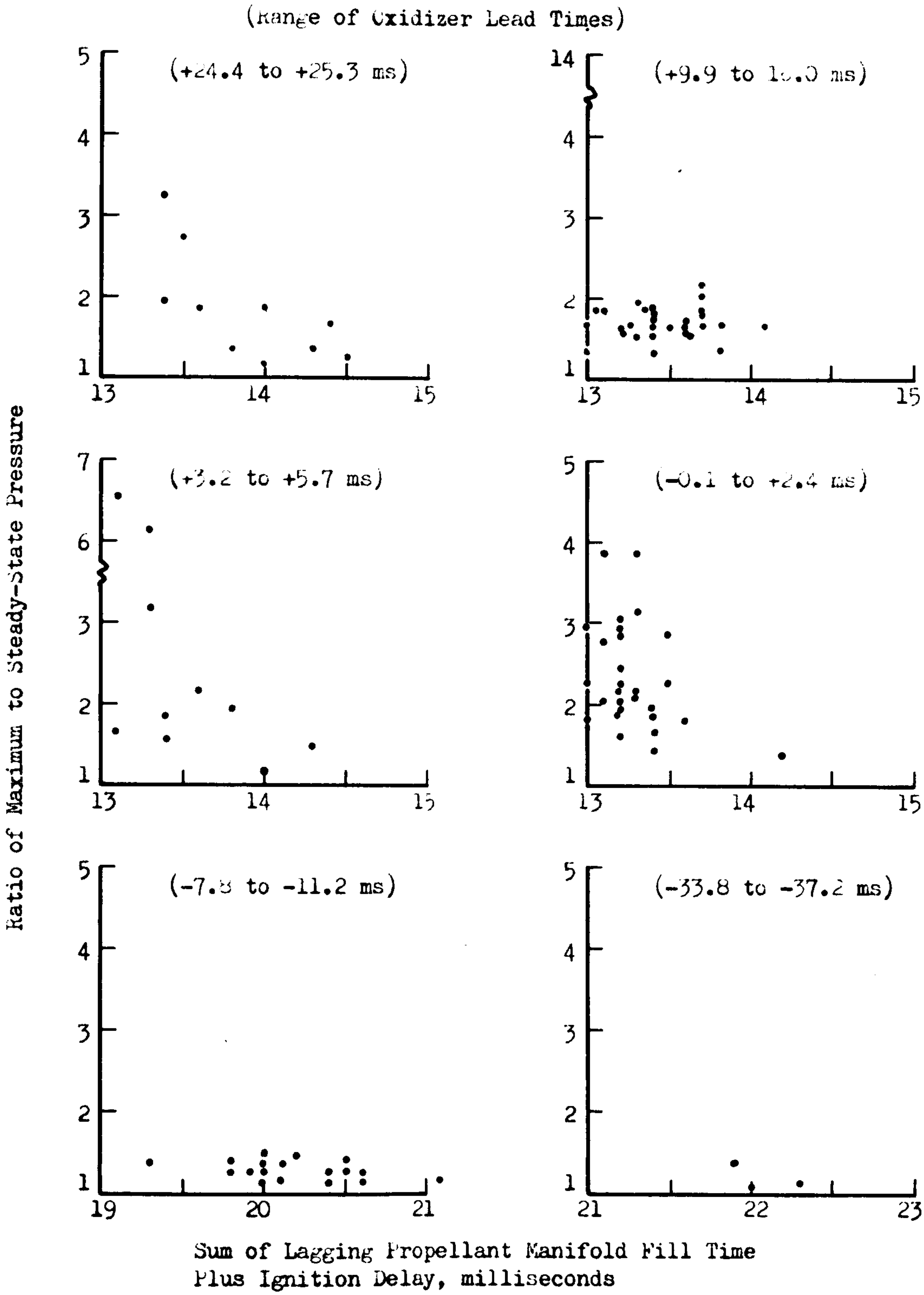
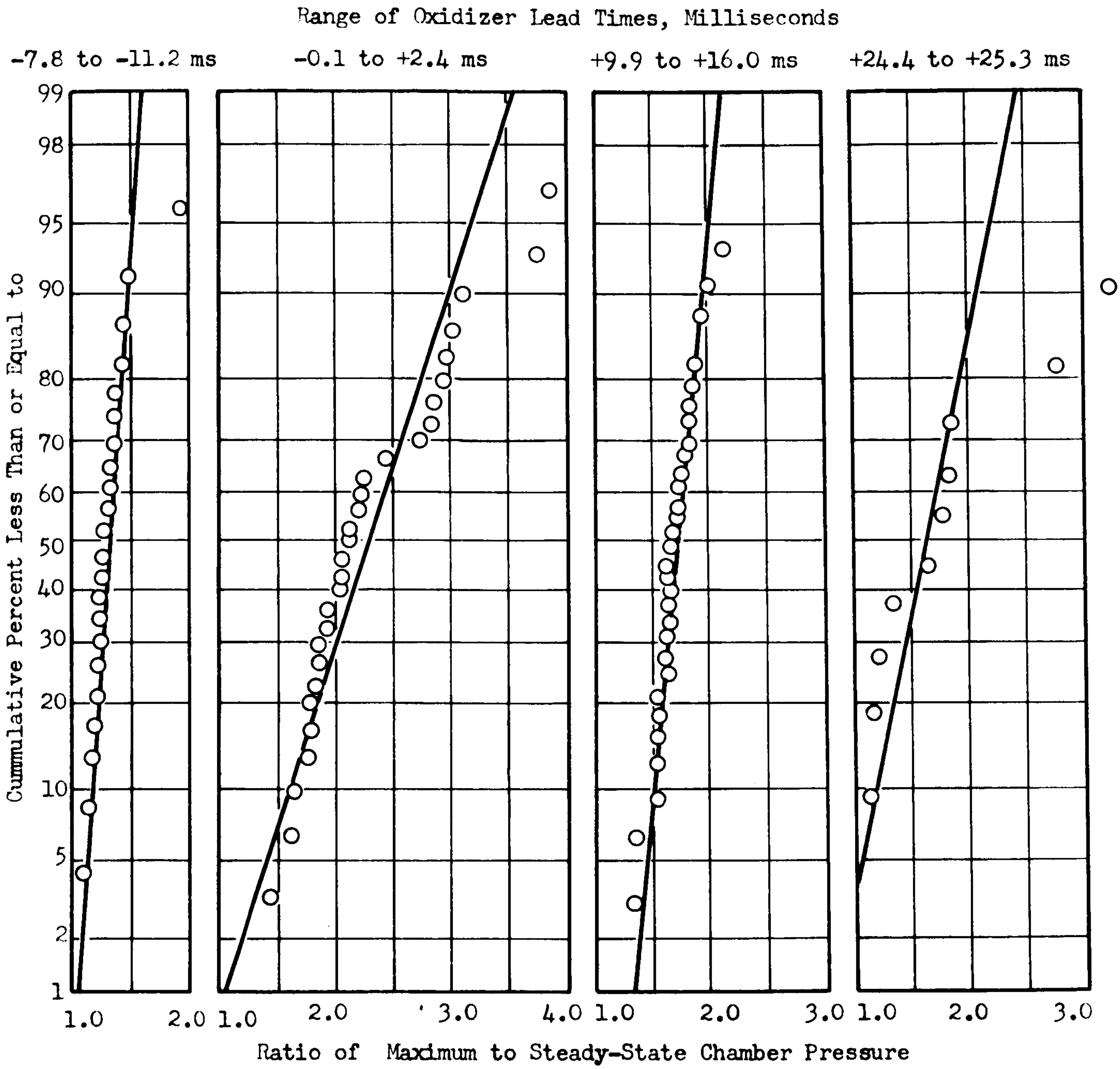
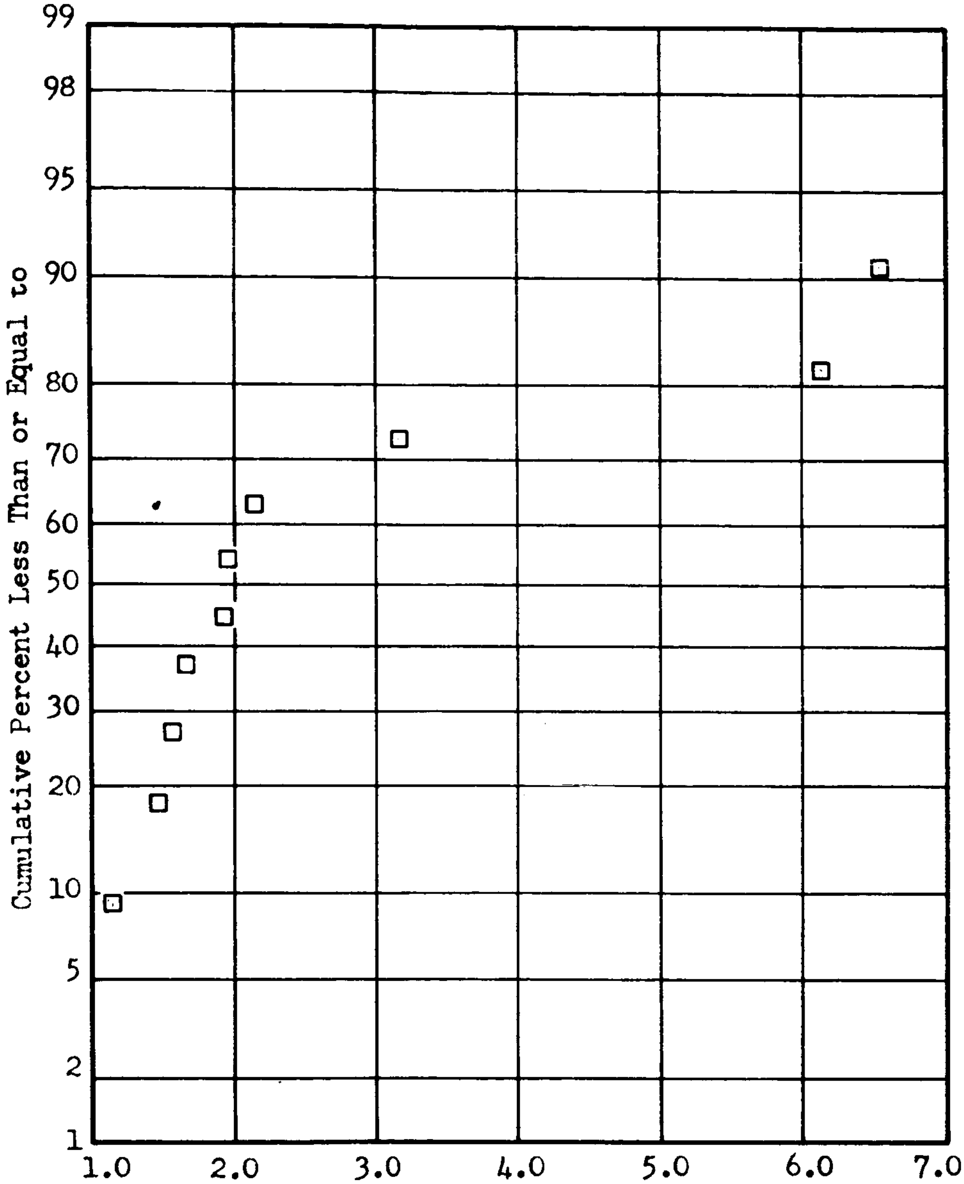



Figure 13. Effect of Ignition Delay on the Spiking Ratio for Various Oxidizer Lead Time Intervals




Propellants: $N_2O_4$/MMH
Mixture Ratio (weight $N_2O_4$/weight MMH): 2.0
Temperature: 100 F - Altitude: 150,000 feet
Steady-State Chamber Pressure: 150 psia

Figure 14. Cumulative Distributions of Spiking Ratios for Various Oxidizer Lead Time Intervals (Probability Scale)




Ratio of Maximum to Steady-State Chamber Pressure

Propellants: $N_2O_4$/MMH
Mixture Ratio (weight $N_2O_4$/weight MMH): 2.0
Temperature: 100 F -- Altitude: 150,000 feet
Steady-State Chamber Pressure: 150 psia

Figure 15. Cumulative Distribution of Spiking Ratios for Oxidizer Lead Times of +3.2 to +5.7 Milliseconds (Probability Scale)

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13. ABSTRACT A study was conducted to compare the noncatalytic altitude ignition characteristics of the $N_2O_4$/MMH and 98 percent $H_2O_2$/MMH propellant combinations. All tests were conducted with a 91-pound-thrust, 150-psia chamber pressure combustor with a 16-element (unlike doublet) splash plate design injector. The simulated altitude was 150,000 feet; nominal temperatures were 100 F. The two firings with the $H_2O_2$/MMH propellants resulted in injector-damaging pressure spikes in the 3500-psi range. These were considerably in excess of the average ignition spikes of 325 psi noted during the 114 $N_2O_4$/MMH tests. The effects of valve timing and ignition delay on spiking for the $N_2O_4$/MMH combination were noted and discussed. For this propellant combination, uncorrected c* efficiencies of approximately 94 percent were found.

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| Attitude Control Engines | | | | | | |
| Nitrogen Tetroxide/Monomethylhydrazine | | | | | | |
| Hydrogen Peroxide/Monomethylhydrazine | | | | | | |